Hermetic Packaging of the LAPPDs
and
Fast Timing Implications for Neutrino-less Double-Beta Decay Searches

Andrey Elagin
University of Chicago

HEP Lunch Seminar 10/28/2013

What is 0νββ?

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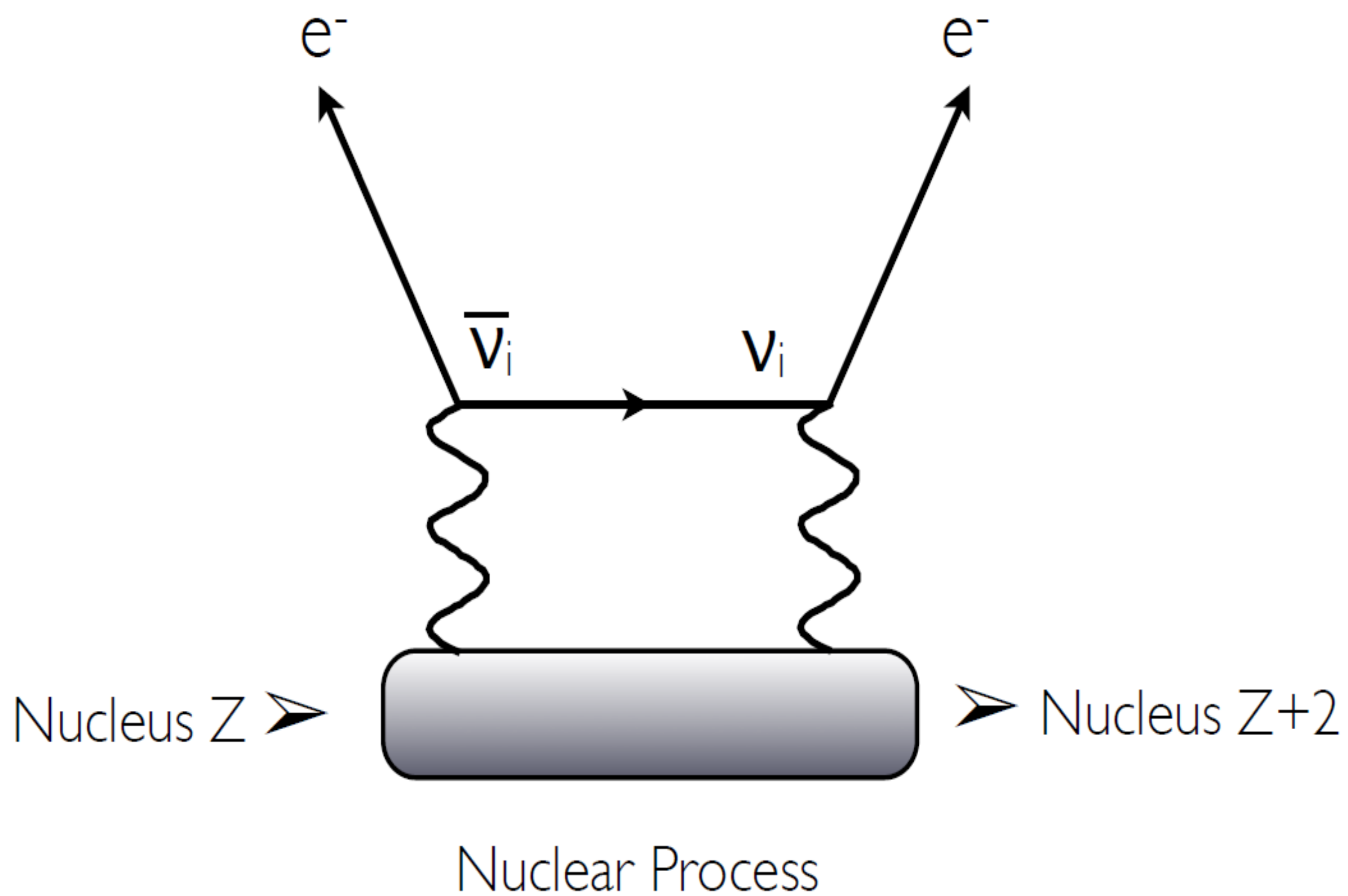

Compare to normal beta decay: Z → (Z+1), e⁻, $\bar{\nu}_e$

Why is it interesting?

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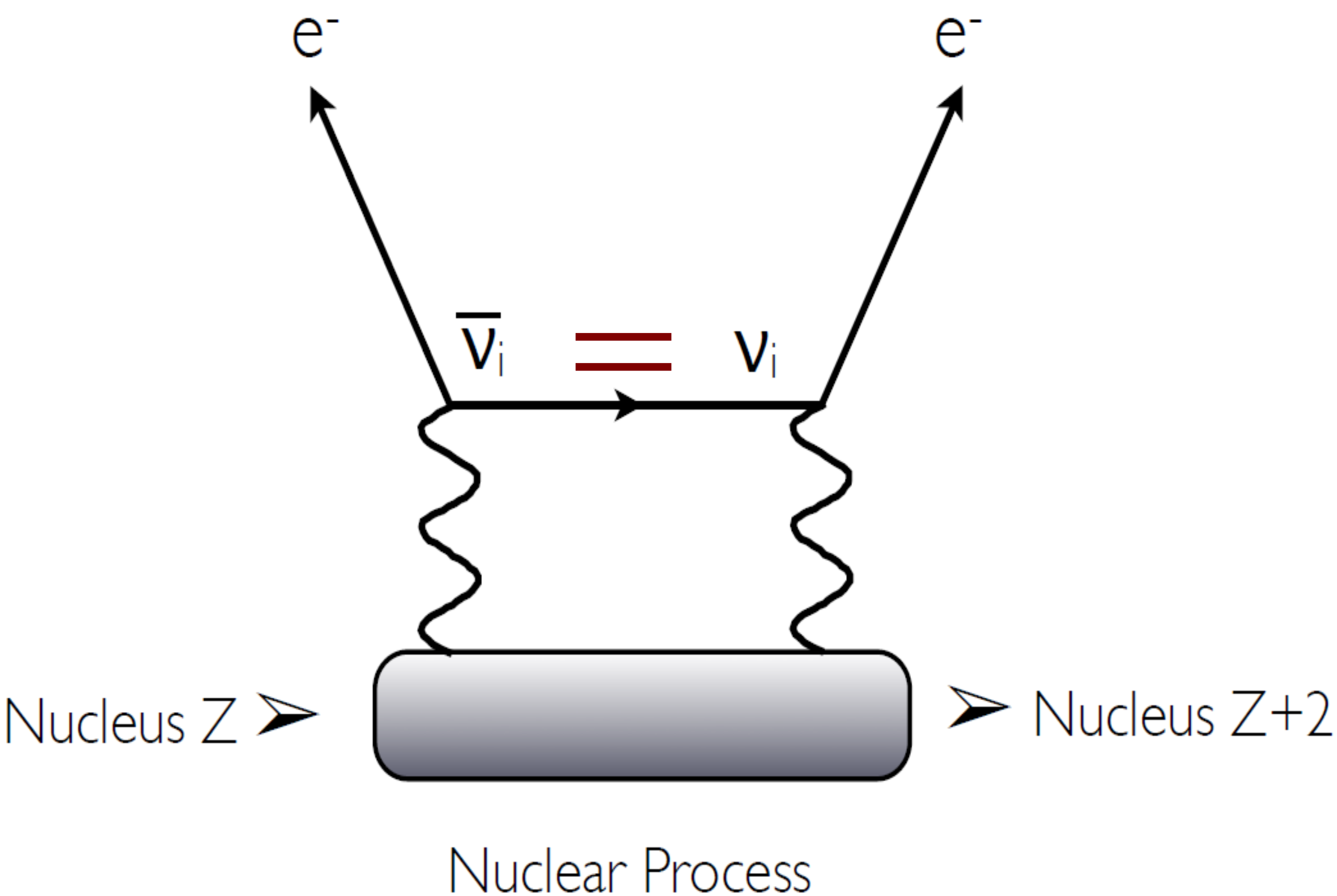

If observed, neutrino is a Majorana particle, i.e. own antiparticle.

Signature: two electrons with well defined total kinetic energy (2-4 MeV)

What are the challenges?

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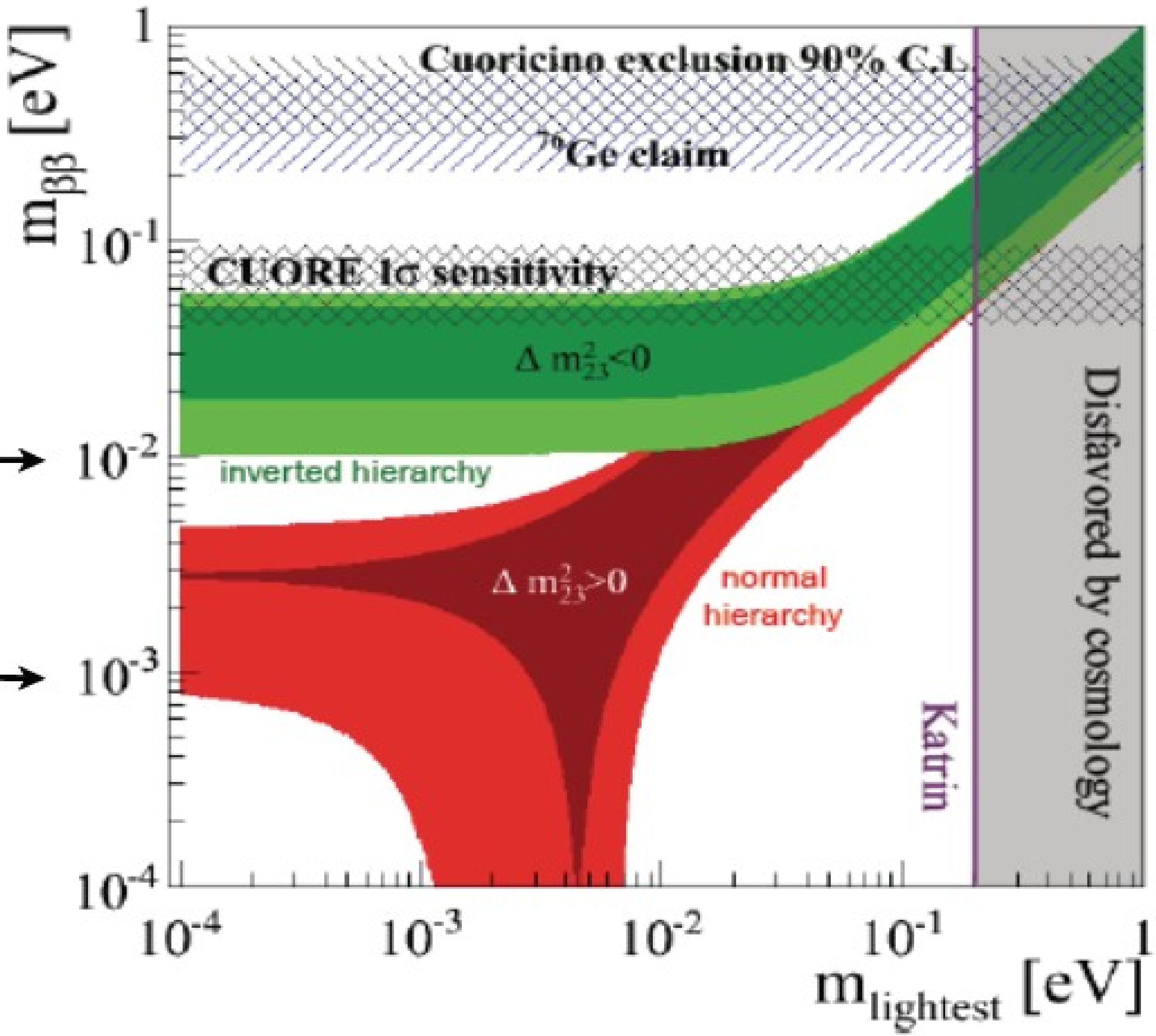
Rare process (e.g. $T_{1/2}[^{136}Xe] > 10^{25}$ years): need to get bigger

$$\Gamma = G\,|M|^2\,|m_{\beta\beta}|^2$$

EXO ~32 kg yr

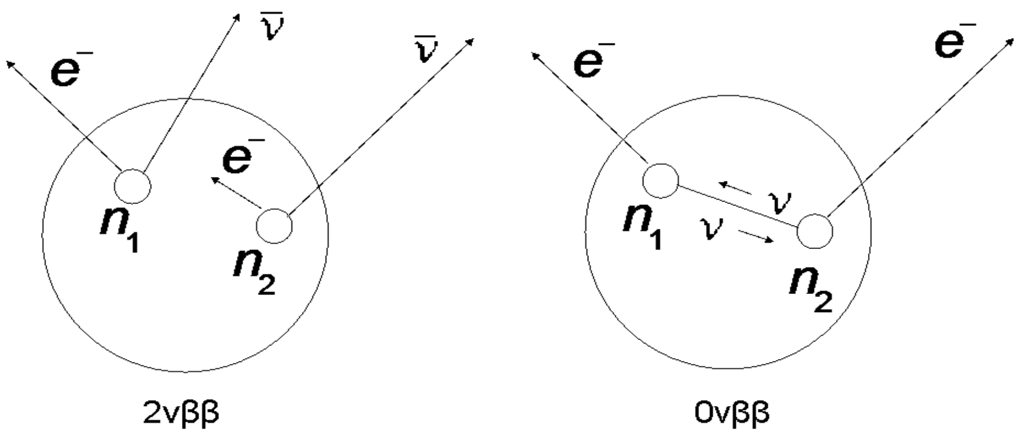
1 ton

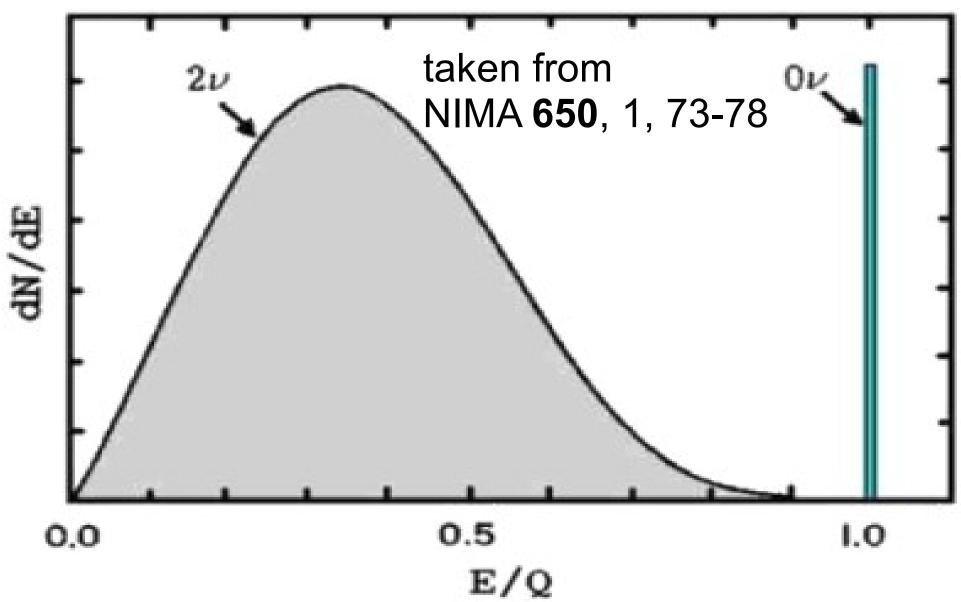
10 ton

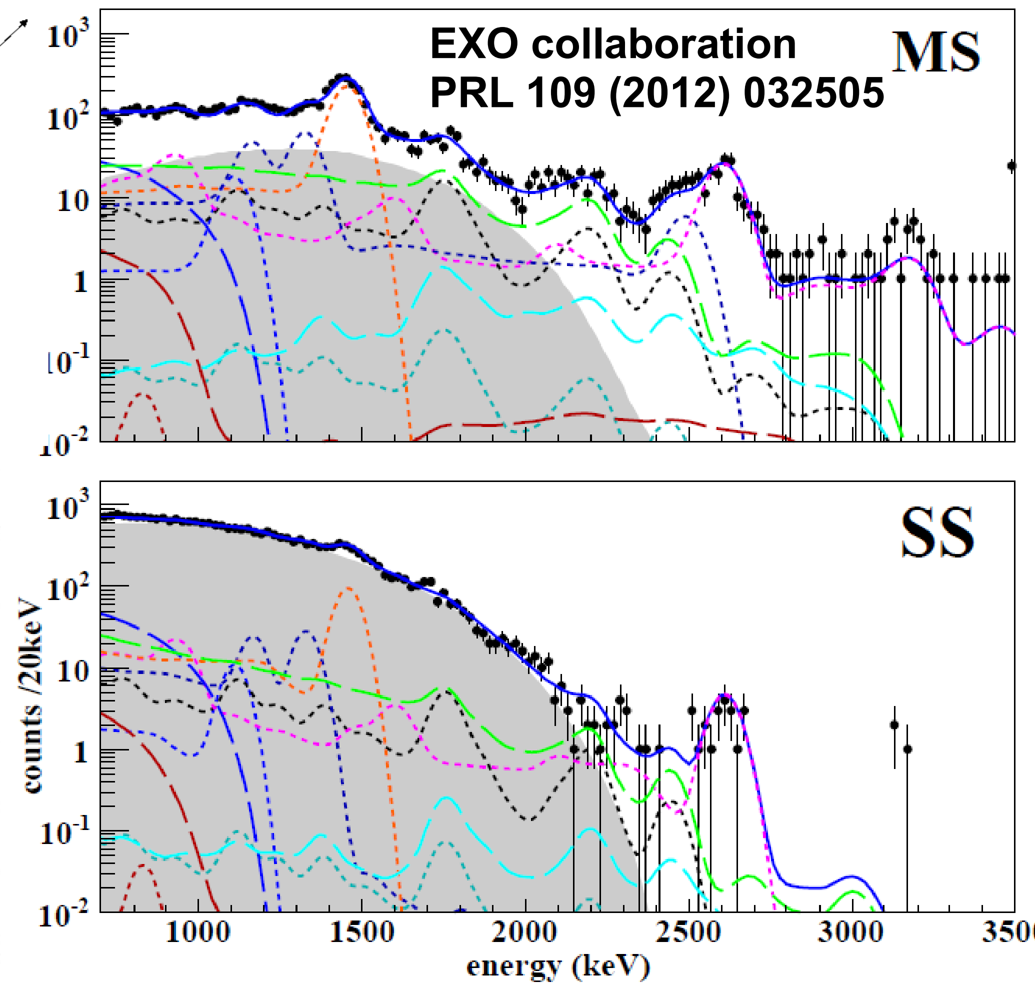


What are the challenges?

Tough backgrounds: need to get smarter







Ideas for 0νββ experiments

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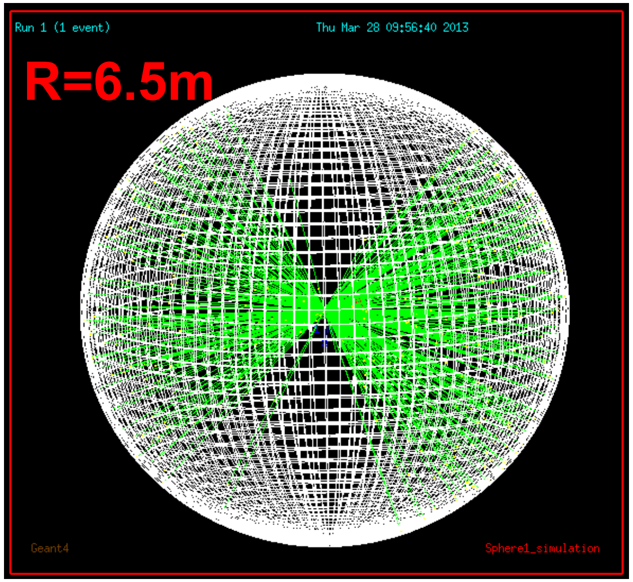
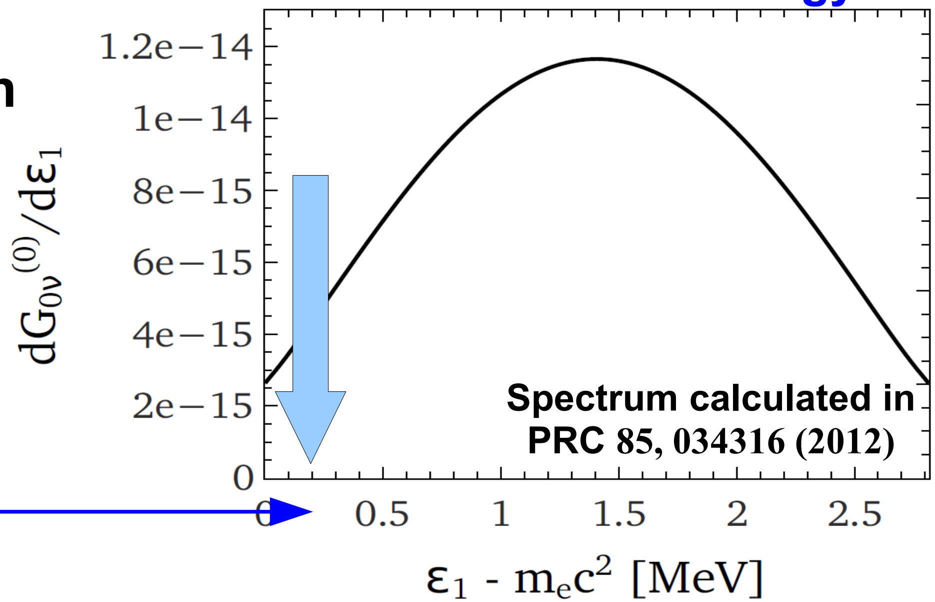
- **Total energy in signal events is well defined.**
- **Use scintillation light for energy measurements**
- **Use event topology to suppress backgrounds**
  - signal is two, mostly, "back-to-back" electrons
- **Electrons are ~1MeV → above Cherenkov threshold**
- **Use Cherenkov light to extract directionality of the two electrons**
  - all light can be used to constrain location of the vertex
  - Cherenkov light arrives early because of longer wavelength and delay of the scintillation process

Simulation of ^{116}Cd 0νββ event



Electron kinetic energy



Cherenkov threshold for n=1.47 →

Emission Spectra

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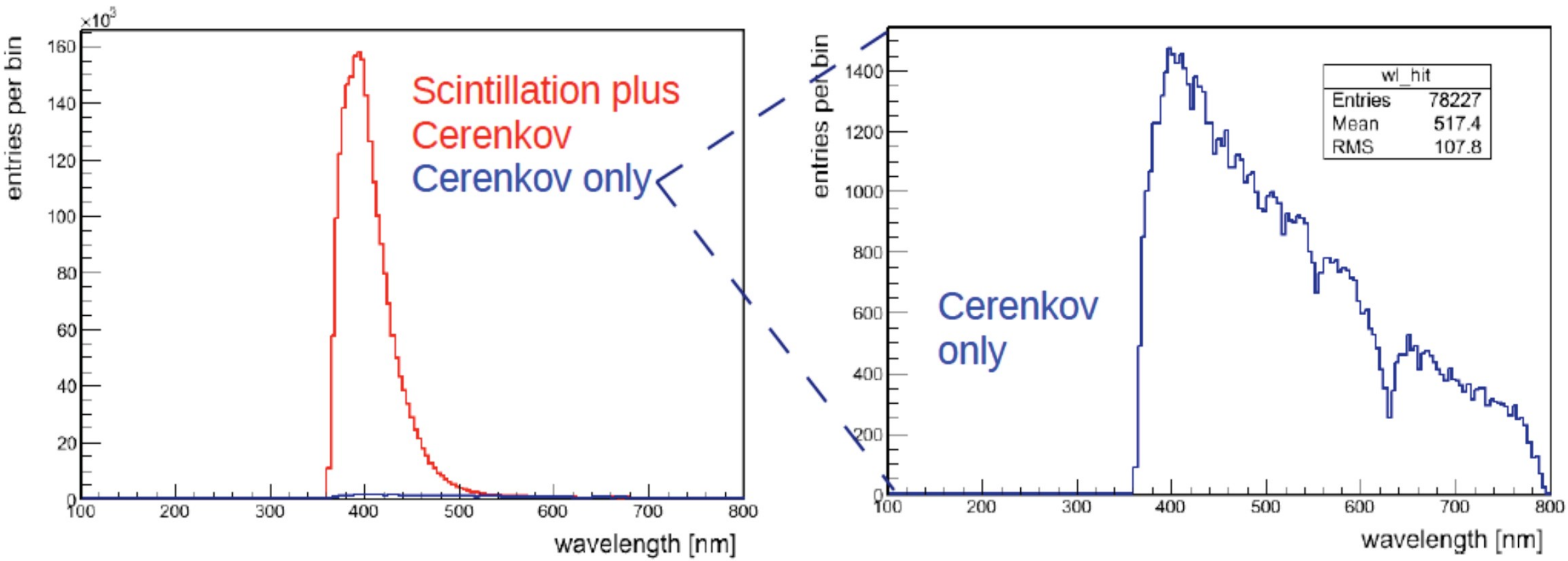
Simulation of 5 MeV electrons in KamLAND scintillator

5 MeV is a little higher for 0νββ search but much lower than typical energies where cherenkov light is being considered.

Seems to be a reasonable choice to test separation between Cherenkov and scintillation



All photons below 360nm get absorbed

Cherenkov vs Scintillation

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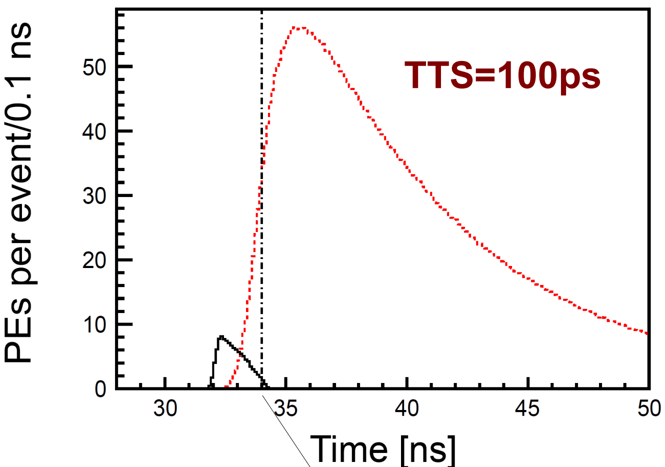
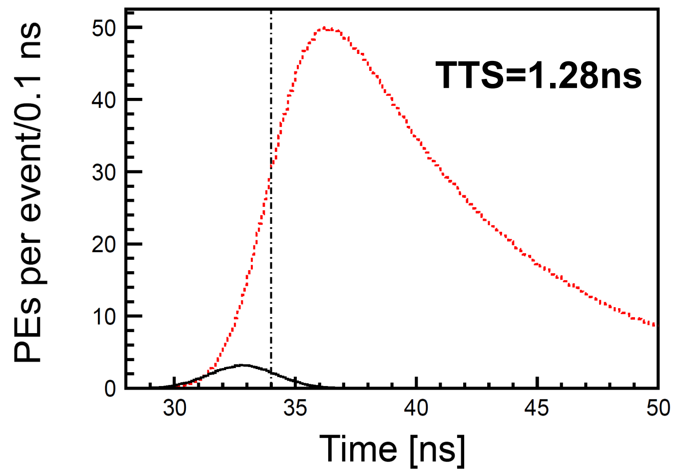
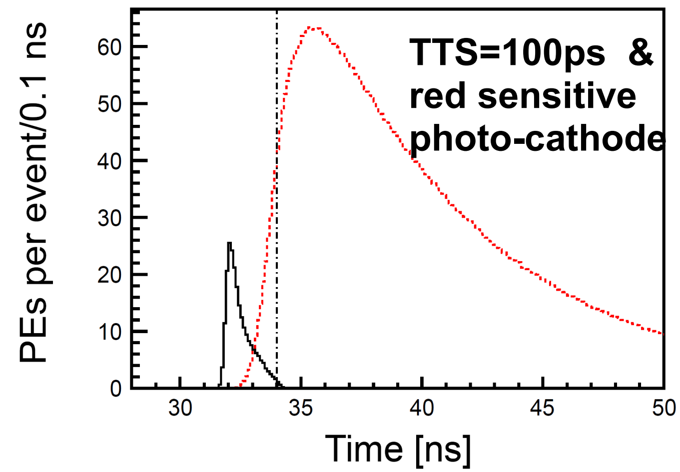
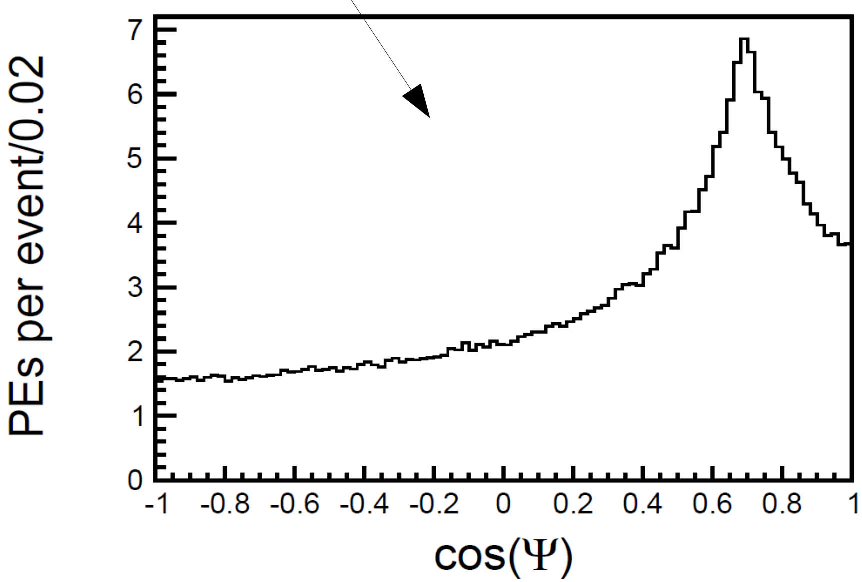
Simulation of 5 MeV electrons in KamLAND scintillator









Use early light to extract directionality

A shift between cherenkov and scintillation spectra is a plus

Reconstruction: vertex

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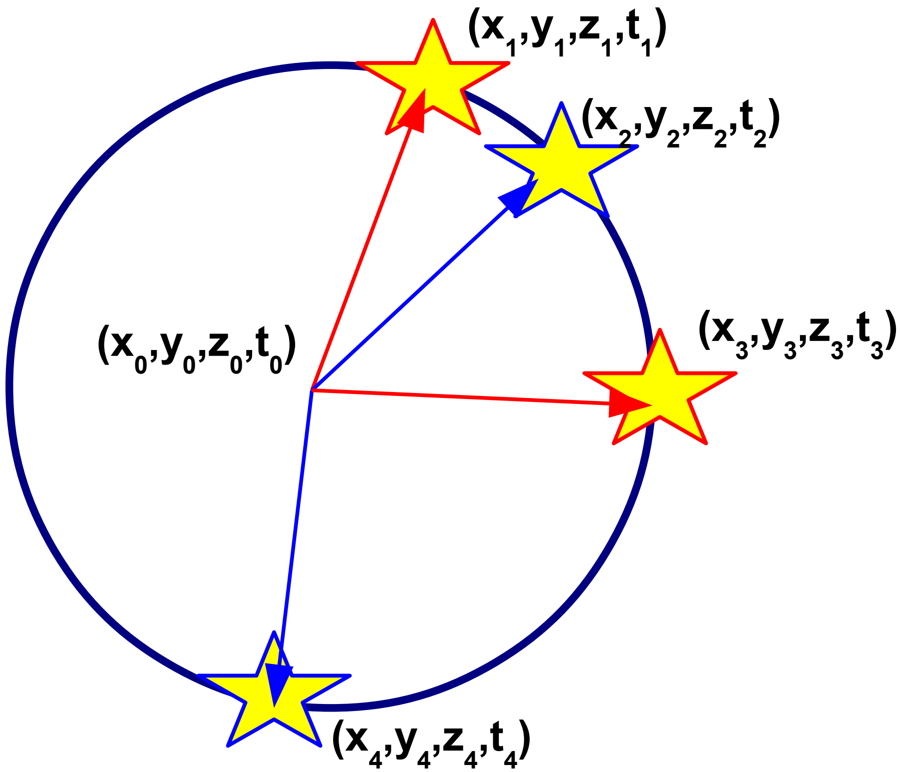
Step 1: find vertex (adapted from water cherenkov)

- *Assume all light is emitted from a single point (~3 cm track in a ~6 m detector)*
- *For light emission from a single point any 4 photons (quadruples) would be sufficient to solve for vertex*
- *With all „real world“ effects we use 400 randomly chosen quadruples and select the one which fits the best to the full ensemble of all photon hits*
- *Goodness of the fit is based on the distribution of „point time residuals“ (the difference between actual hit time and predicted time of flight from the vertex)*



For i=1...4:

$$(x_i-x_0)^2 + (y_i-y_0)^2 + (z_i-z_0)^2 = v(t_i-t_0)^2$$

v **is the speed of light in the media**

Time residuals $dT = (t_j-t_0)$,

where $j=1...N_{all}$

The most narrow dT distribution is the closest to the true vertex

Reconstruction: direction

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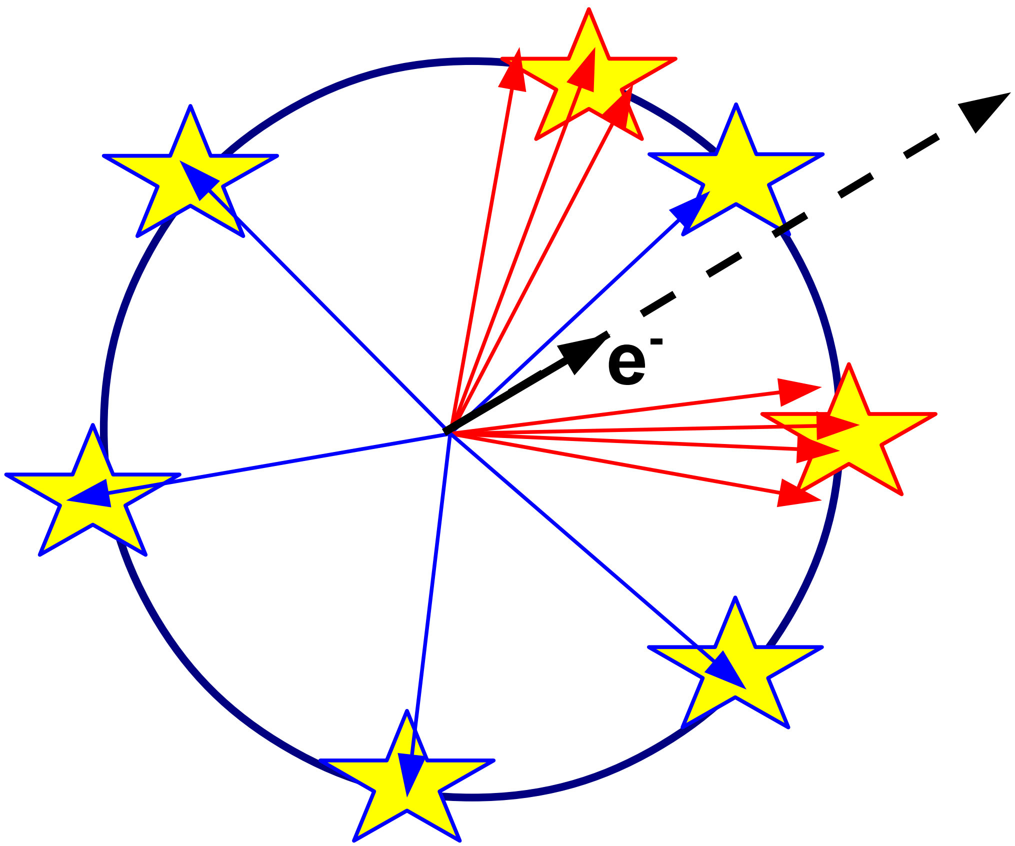
Step 2: find direction

- Cherenkov light is directional
- Timing cut enhances the purity of the Cherenkov light
- The centroid of all vectors pointing from the vertex is a good measure of the direction of the track



Directionality of 5 MeV e^-

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arxiv:1307.5813

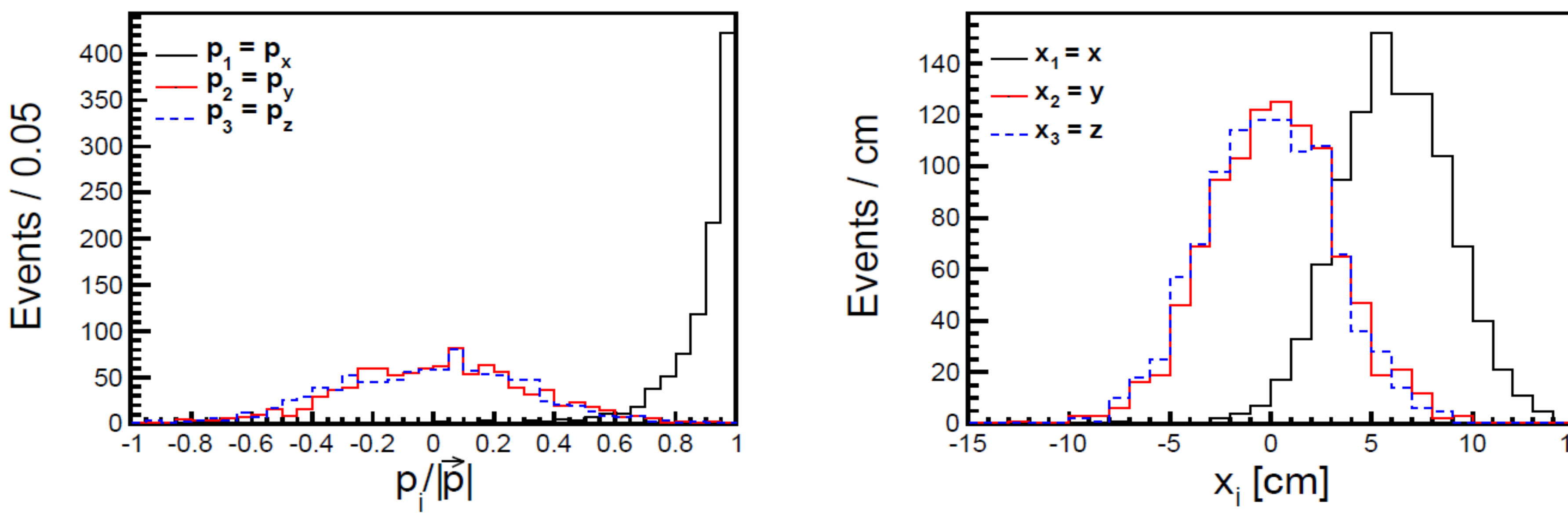
Measuring Directionality in Double-Beta Decay and Neutrino Interactions with Kiloton-Scale Scintillation Detectors

C. Aberle,[1] A. Elagin,[2] H. J. Frisch,[2] M. Wetstein,[2] and L. Winslow[1]

[1]*University of California Los Angeles, Los Angeles, CA 90095, USA*
[2]*University of Chicago, Chicago, IL 60637, USA*

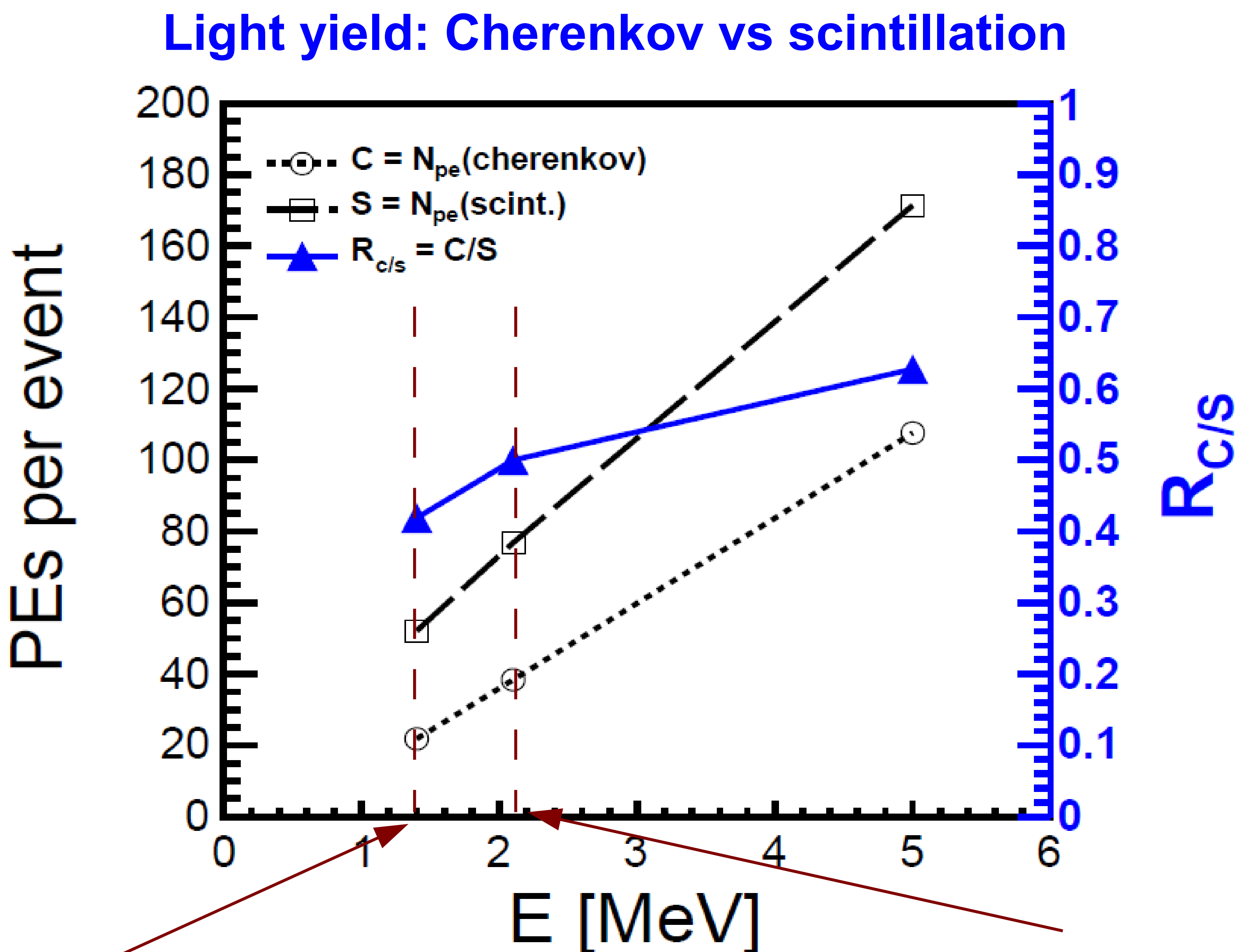
(Dated: July 23, 2013)

Large liquid-scintillator-based detectors have proven to be exceptionally effective for low energy neutrino measurements due to their good energy resolution and scalability to large volumes. The addition of directional information using Cherenkov light and fast timing would enhance the scientific reach of these detectors, especially for searches for neutrino-less double-beta decay. In this paper, we develop a technique for extracting particle direction using the difference in arrival times for Cherenkov and scintillation light, and evaluate several detector advances in timing, photodetector spectral response, and scintillator emission spectra that could be used to make direction reconstruction a reality in a kiloton-scale detector.



5 MeV electrons are very promising even with a very simple reconstruction

What about Lower Energies?



½ Q (^{116}Cd) =1.4 MeV

½ Q (^{48}Ca) =2.1 MeV

What about Lower Energies?

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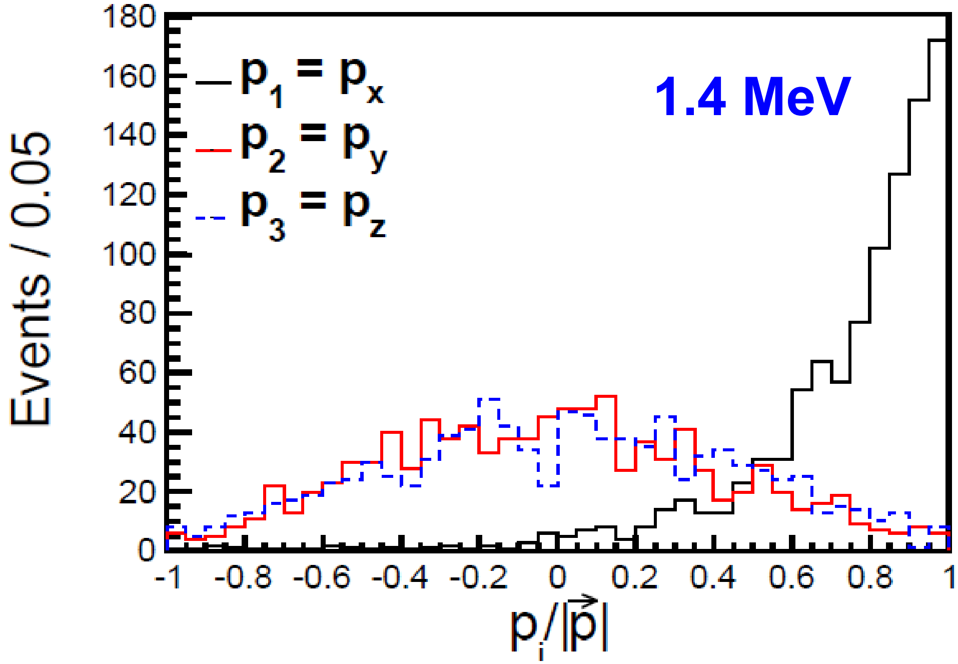

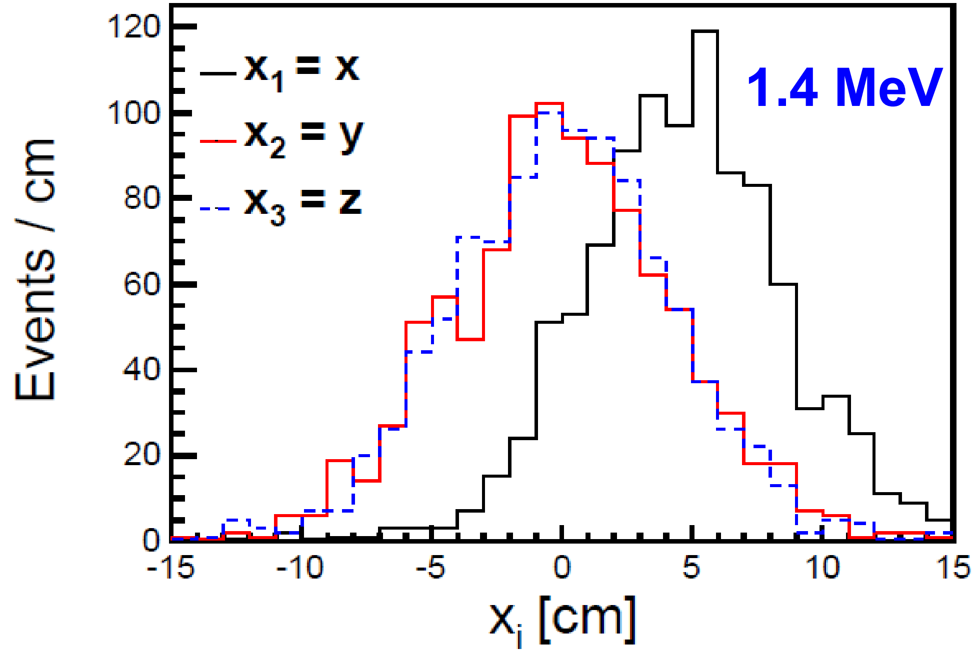

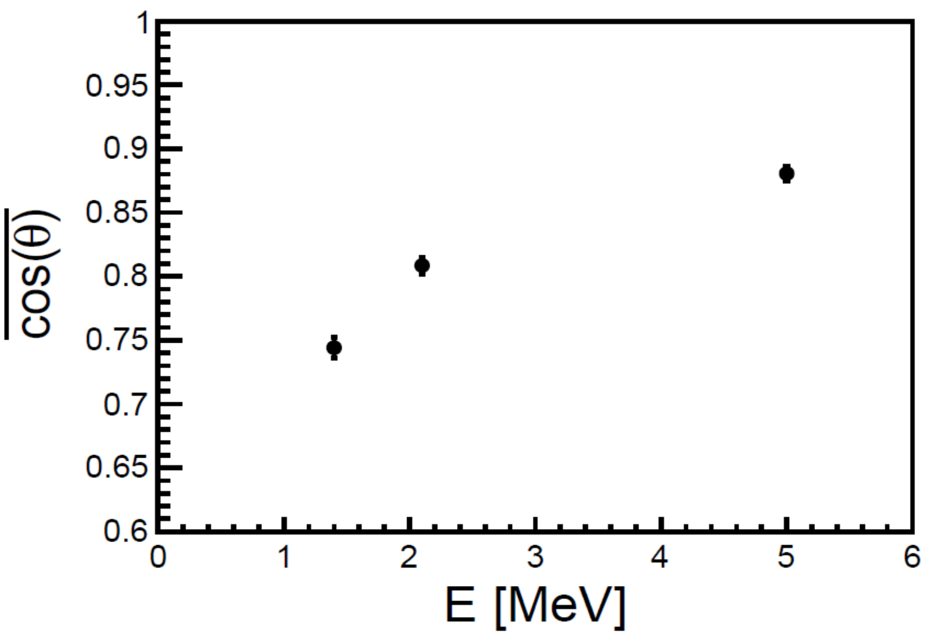

- *With 100ps timing, the vertex is constrained within 4-6 cm and the directional information can be extracted even for ~1MeV electrons*
- *The next major step is to compare „back-to-back“ $0\nu\beta\beta$ events with $2\nu\beta\beta$ background*

Candidate Isotopes for 0νββ

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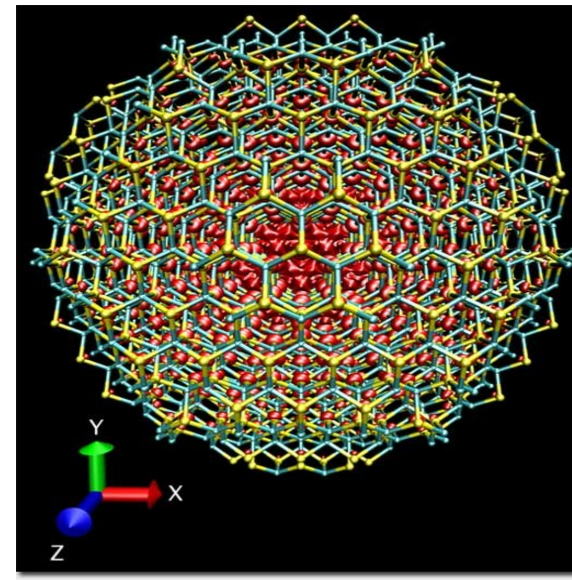
Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.0035%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.533 MeV	34.5%
^{136}Xe	2.479 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%
^{128}Te	0.868 MeV	31.7%

Quantum dot doped scintillators



Common materials are CdS, CdSe, CdTe

Advantage of quantum dot doping:

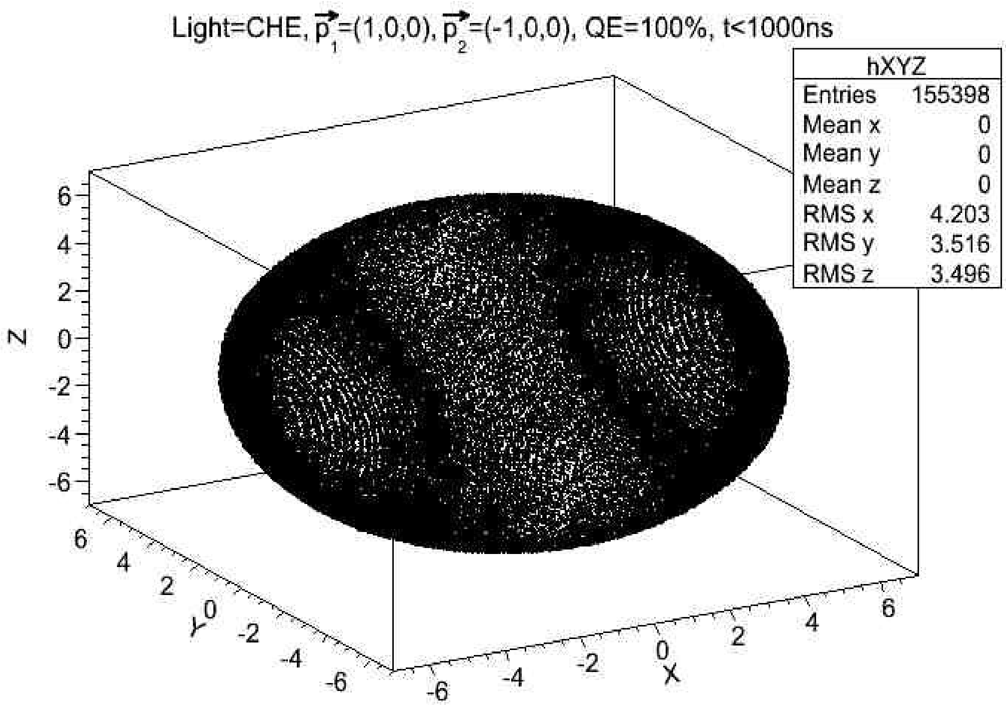
- Narrow the scintillation spectrum
- Shift scintillation spectrum to shorter wavelength
- Dope with metals which can undergo 0vbb

Work by UCLA group C.Aberle, J.J.Li, S.Weiss, and L.Winslow

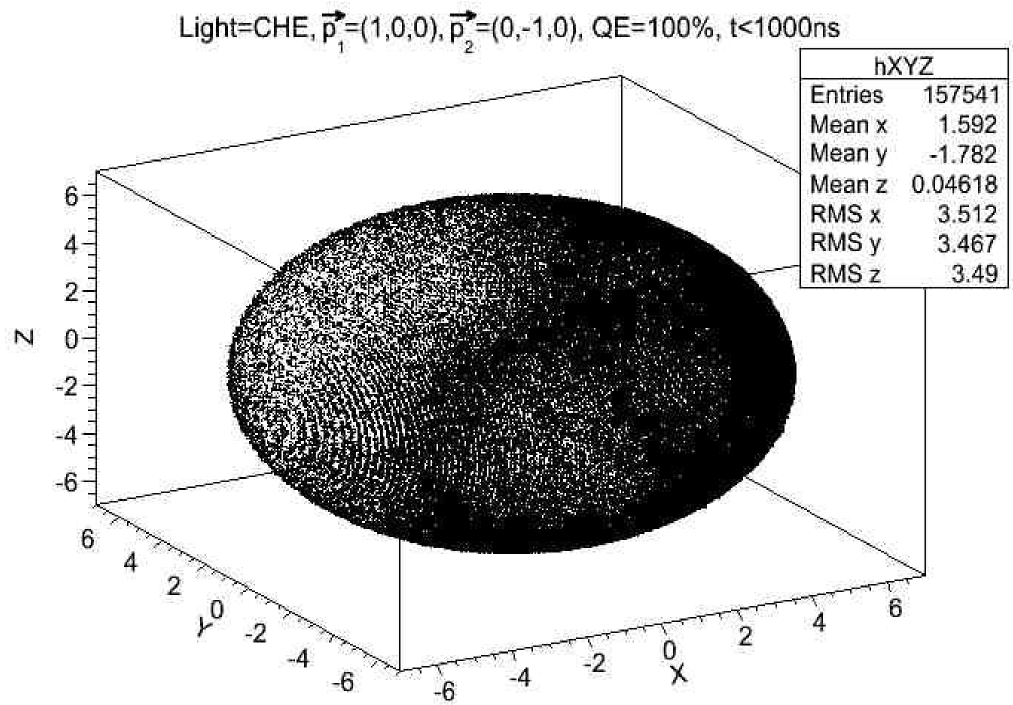
This is another lunch topic!

Event Topology

100 „signal-like“ events
(5MeV electrons back-to-back)



100 „bkg-like“ events
(5MeV electrons at 90 degree)



Cherenkov light only, no time cut, 100% light collection

Spherical Harmonics

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Real-value basis:

$$Y_{\ell m} = \begin{cases} \frac{1}{\sqrt{2}}\left(Y_\ell^m + (-1)^m Y_\ell^{-m}\right) = \sqrt{2} N_{(\ell,m)} P_\ell^m(\cos\theta)\cos m\varphi & \text{if } m > 0 \\ Y_\ell^0 & \text{if } m = 0 \\ \frac{1}{i\sqrt{2}}\left(Y_\ell^{-m} - (-1)^m Y_\ell^m\right) = \sqrt{2} N_{(\ell,|m|)} P_\ell^{|m|}(\cos\theta)\sin|m|\varphi & \text{if } m < 0. \end{cases}$$

$$f(\theta,\varphi) = \sum_{\ell=0}^{\infty}\sum_{m=-\ell}^{\ell} f_{\ell m} Y_{\ell m}(\theta,\varphi).$$

$$N_{(\ell,m)} \equiv \sqrt{\frac{(2\ell+1)}{4\pi}\frac{(\ell-m)!}{(\ell+m)!}}.$$

$$f_\ell^m = \int_\Omega f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi)\, d\Omega = \int_0^{2\pi} d\varphi \int_0^\pi d\theta\, \sin\theta f(\theta,\varphi) Y_\ell^{m*}(\theta,\varphi).$$

L2 norm

$$\int_\Omega |f(\Omega)|^2 d\Omega = \sum_{\ell=0}^{\infty} S_{ff}(\ell)$$

„Power“ (rotation invariant)

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$

Spherical Harmonics for back-to-back vs 90 degree topologies

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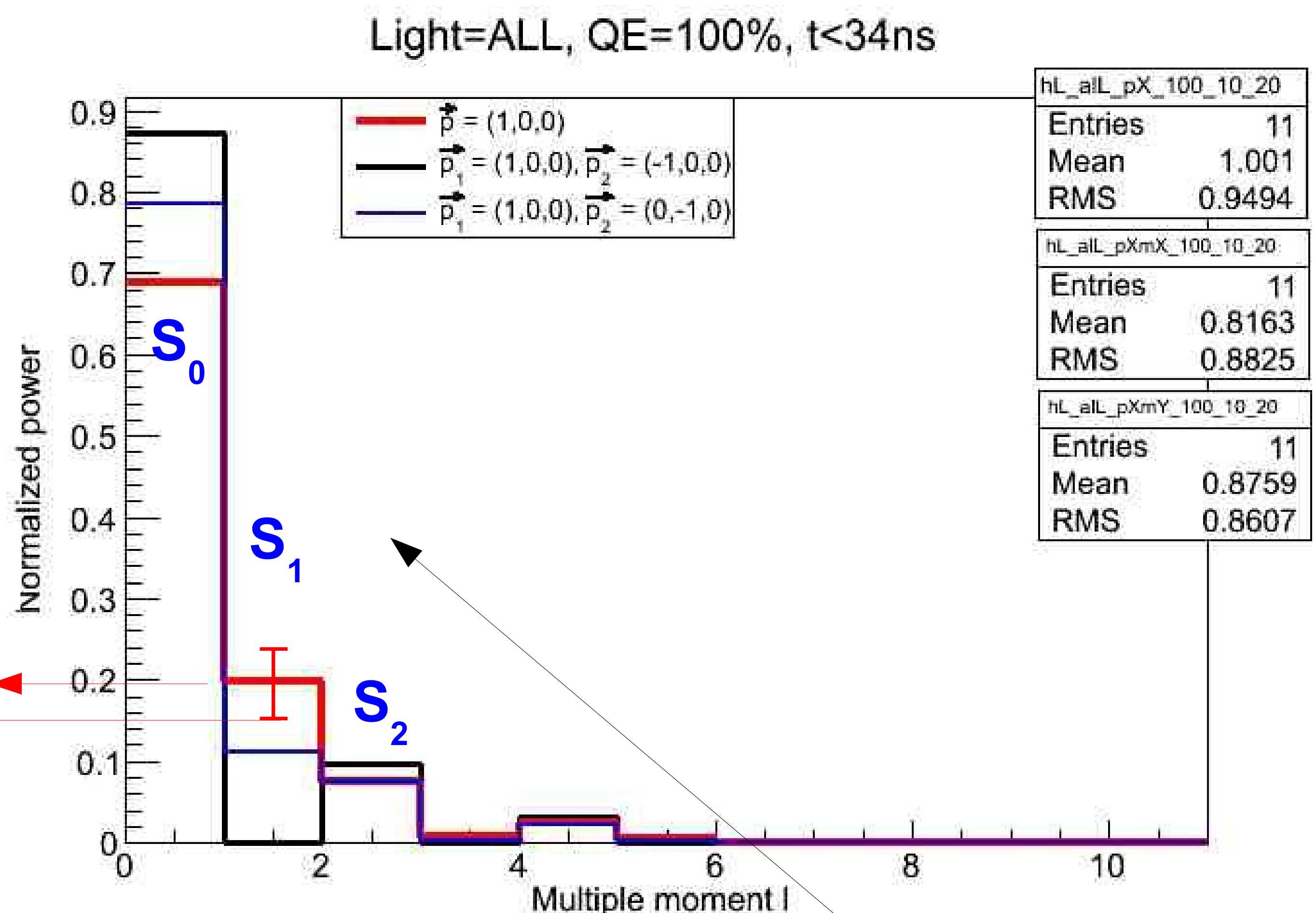
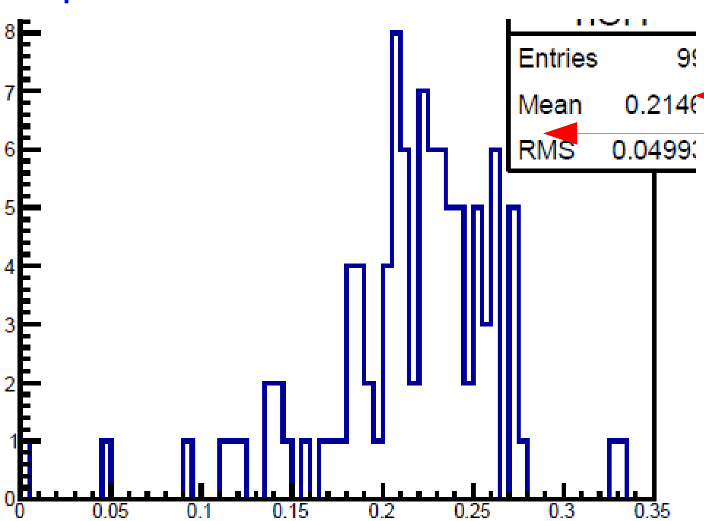
- *Look for the difference between* ***black (back-to-back)*** *and* ***blue (90-degree)*** *lines.*
- ***Red line*** *is for comparison with single electron events*

$$S_{ff}(\ell) = \sum_{m=-\ell}^{\ell} |f_{\ell m}|^2$$

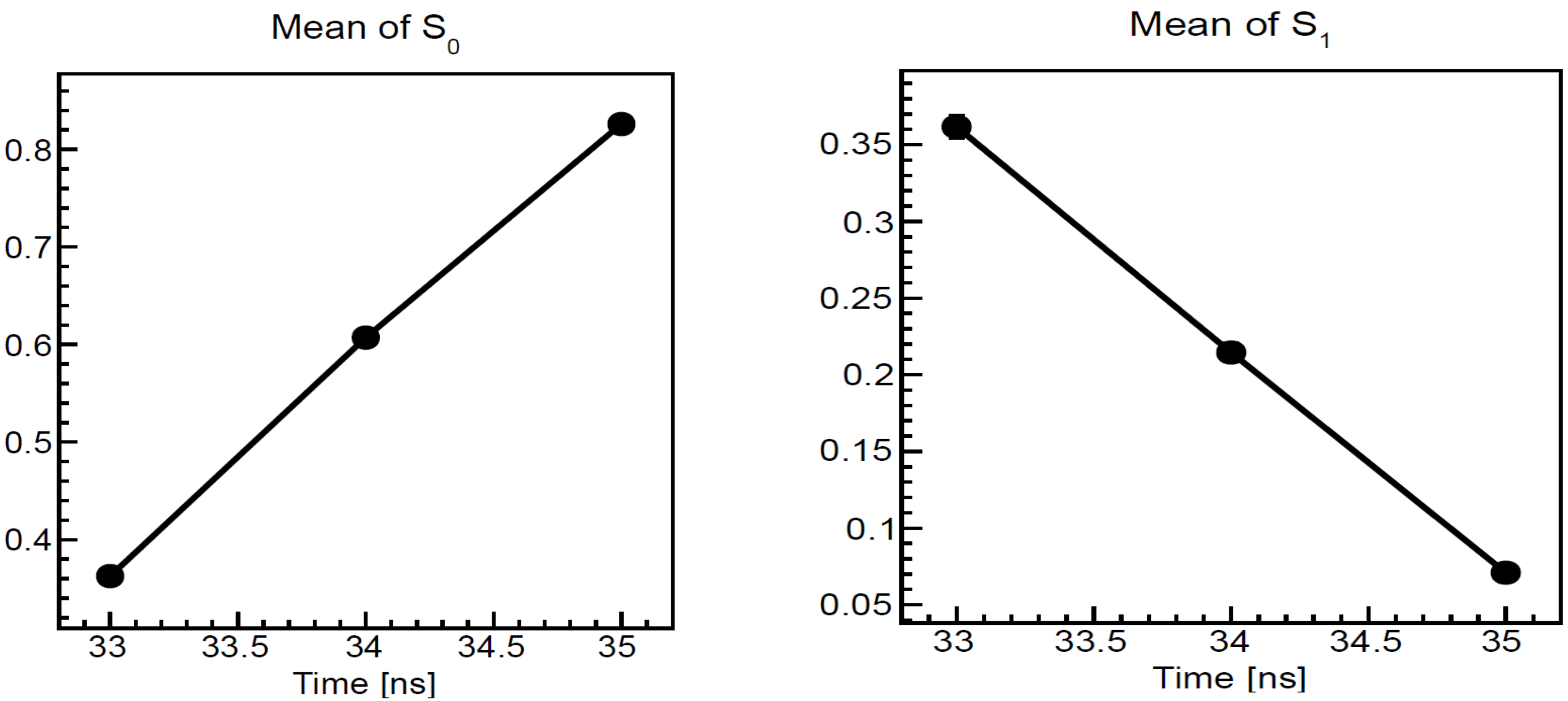


S_1 event-by-event fluctuations



These S_l are calculated for combined hit distribution of 100 events

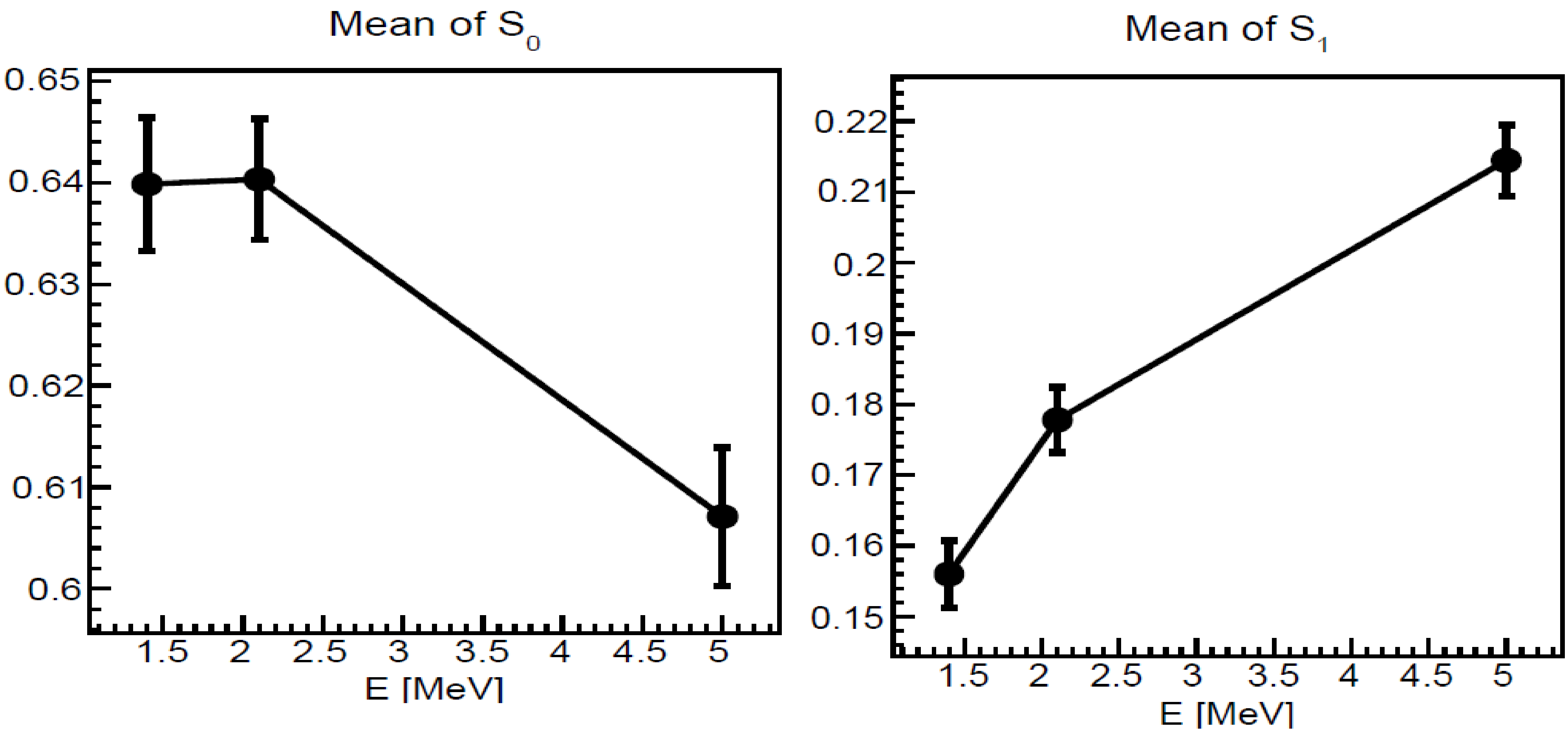
S_l as function of time cut



I like this strong dependence on time because

with fast photo-detectors we may be able to follow the time evolution of spherical harmonics and use this information in reconstruction

S_l as function of electron energy



Note Y axis range, the dependence isn't too strong

What's Next?

- *Compare simulated $0\nu\beta\beta$ events with $2\nu\beta\beta$*
- *Consider events off center*

Now, I will talk about LAPPD and Hermetic Packaging

Large Area Picosecond Photo Detectors

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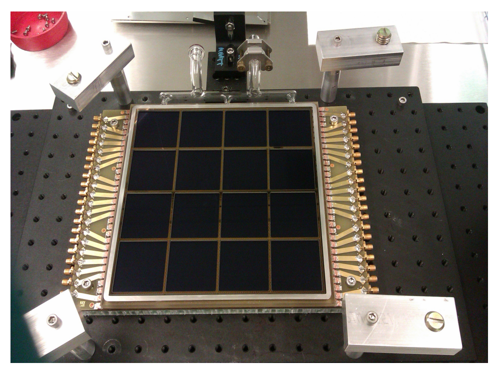
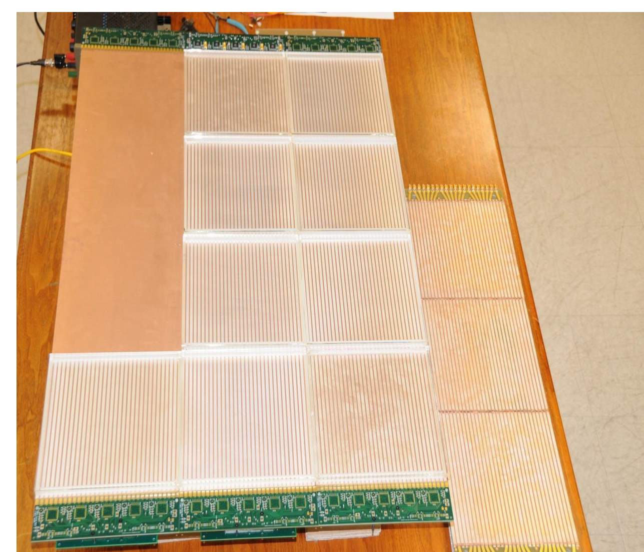
Transformational Change

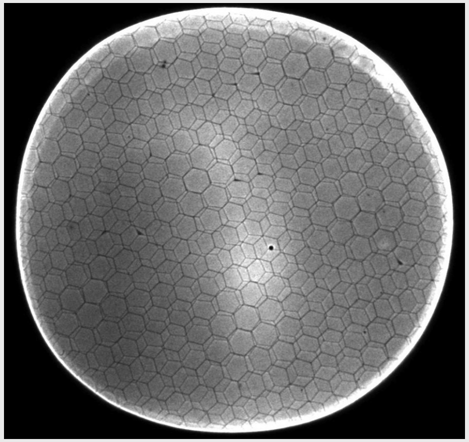
- *Large area*
- *Fast timing*
- *Inexpensive*



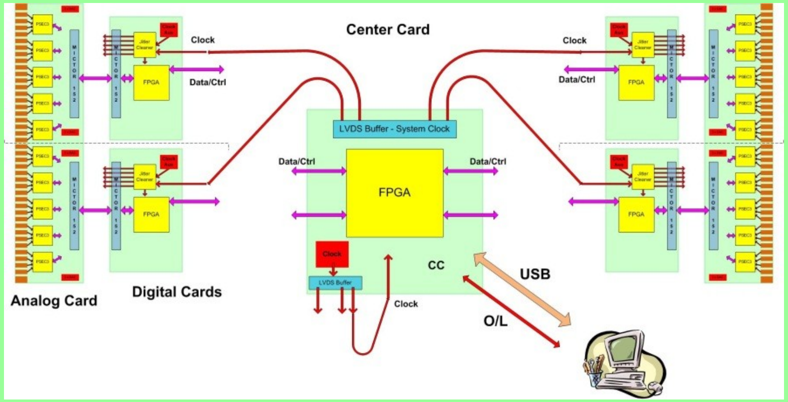


LAPPD Components

MicroChannel Plates

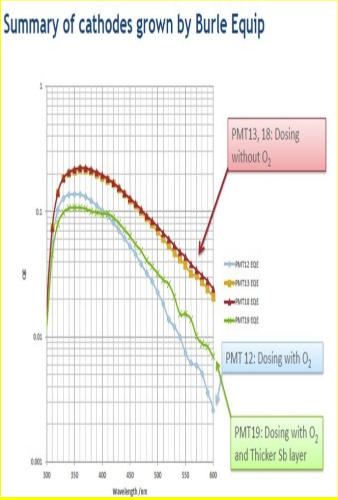


Electronics/Integration



Hermetic Packaging

Photocathodes



Glass Package (20x20cm^2)

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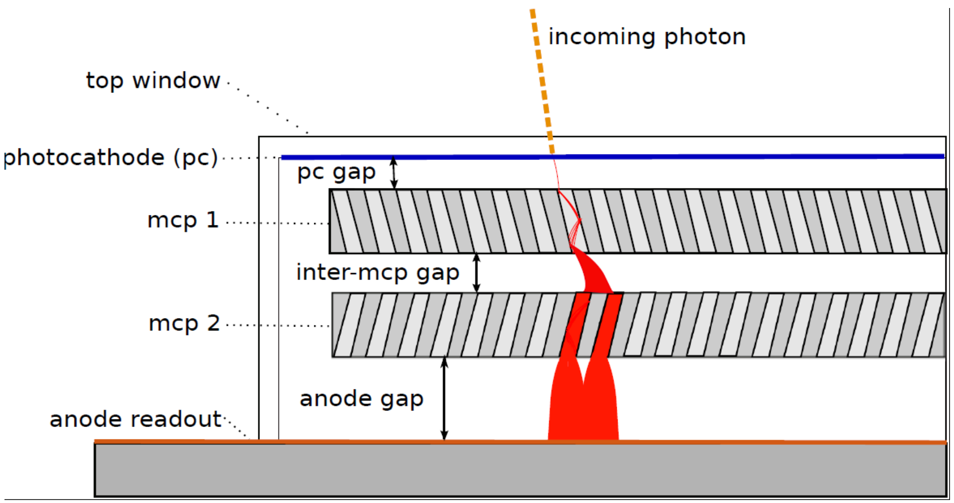
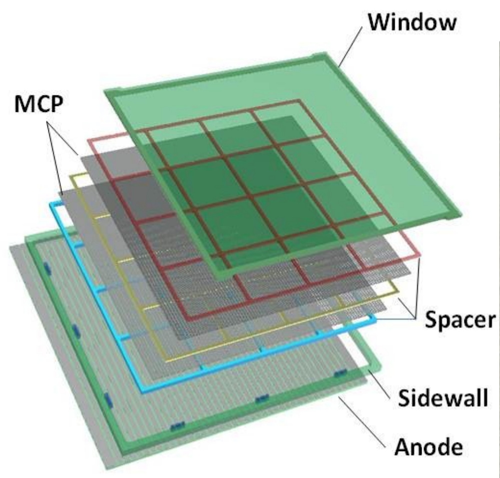
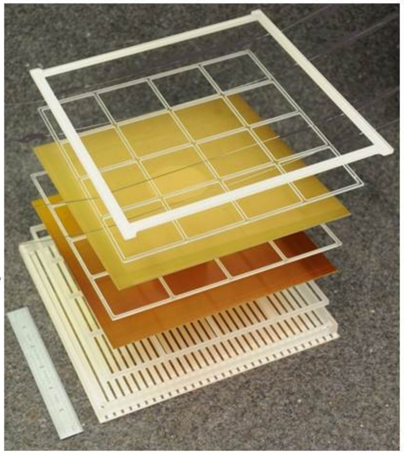


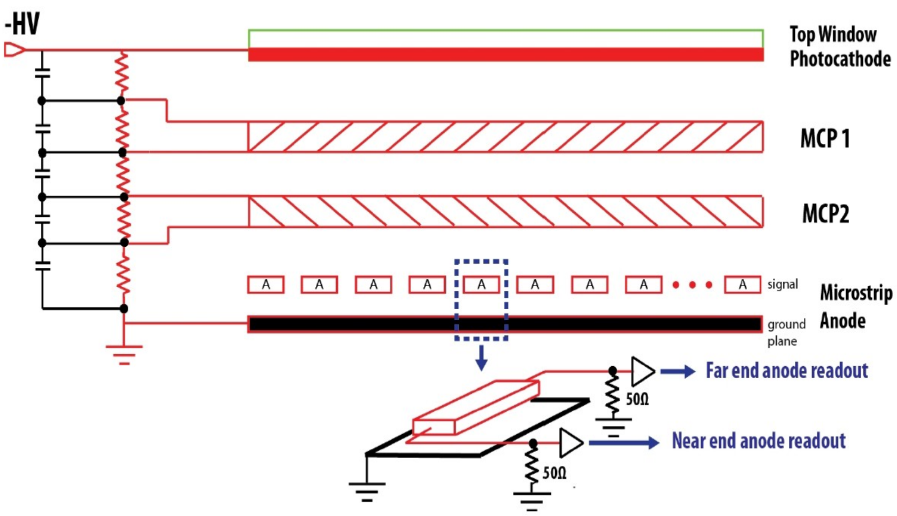


Design Drawing - September 2010



Actual Glass Parts - April 2012

The Frugal Tile



- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object
  - designed for fast timing

Ceramic body packaging is a parallel (and collaborative) effort at Berkeley SSL

MCP Fundamentals

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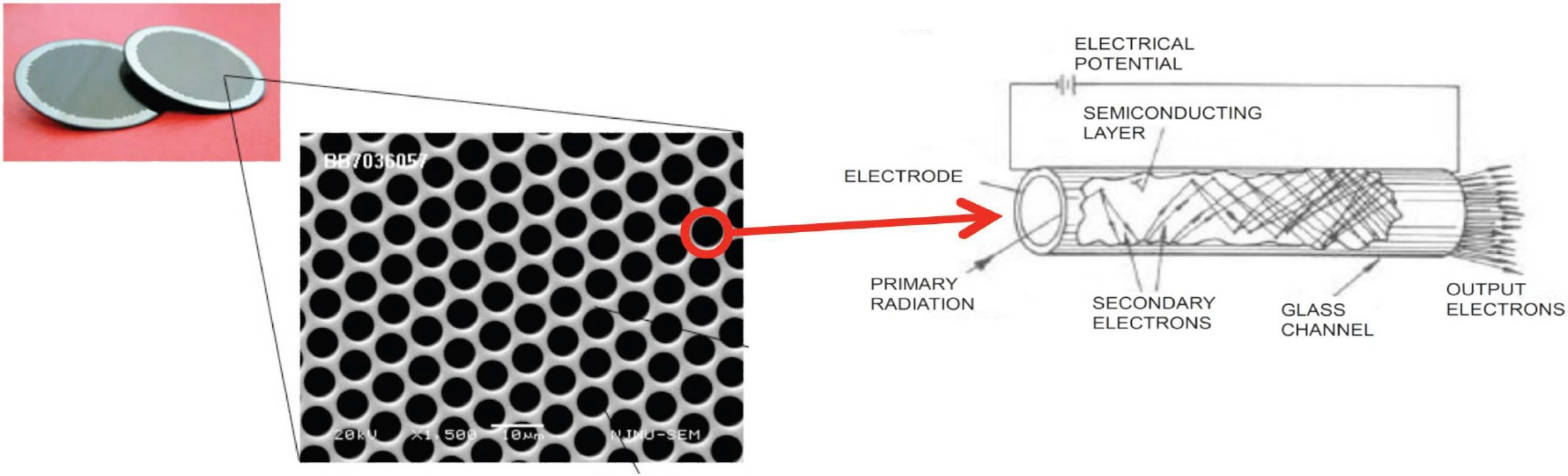
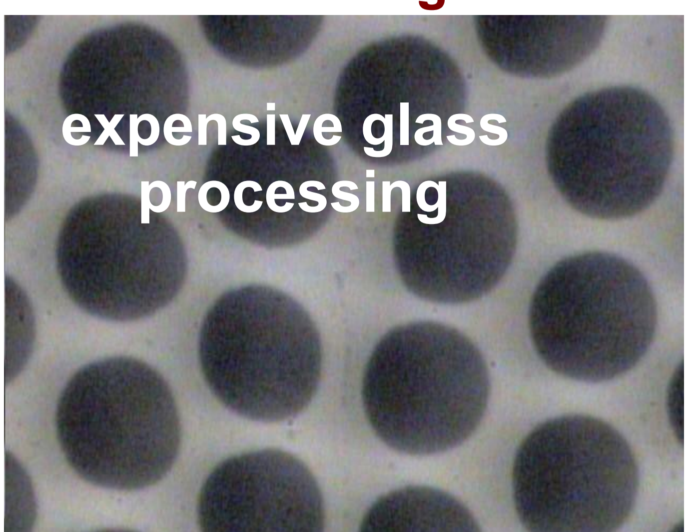


Conventional Pb-glass MCP

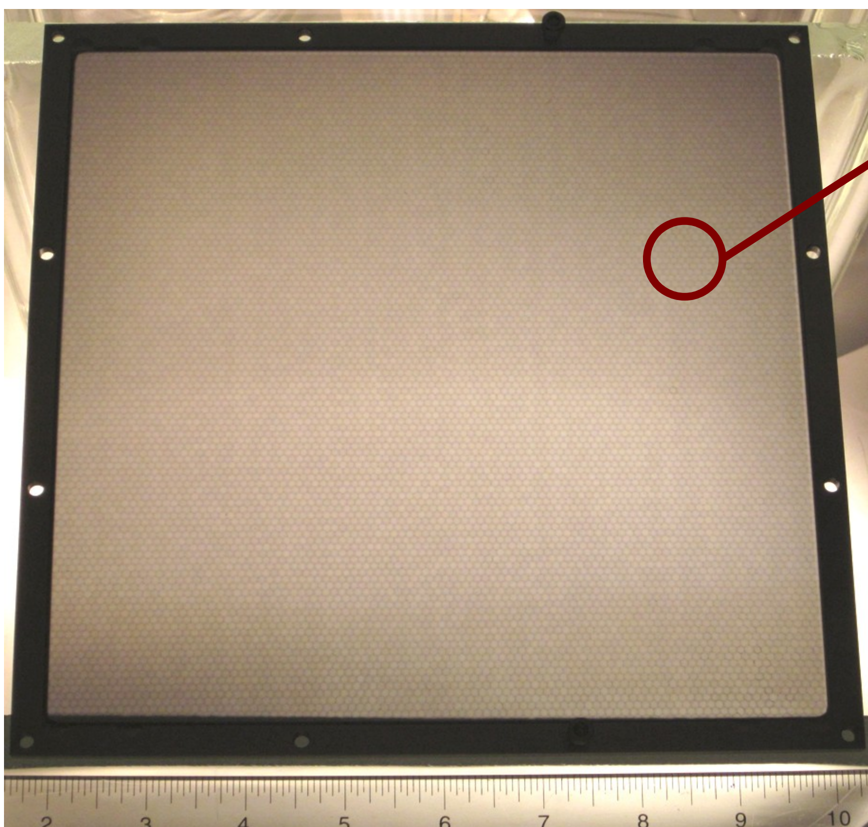


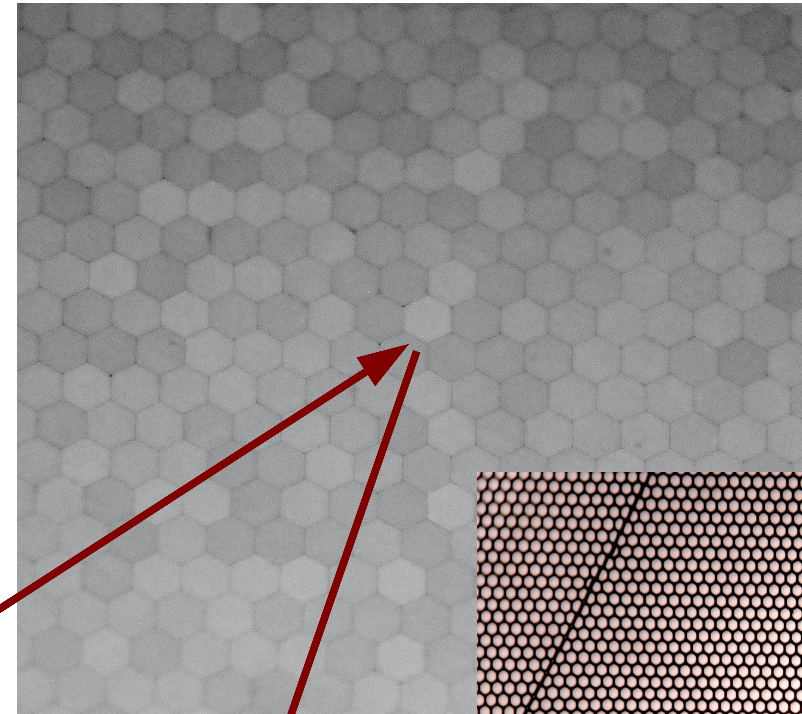
Incom glass substrate

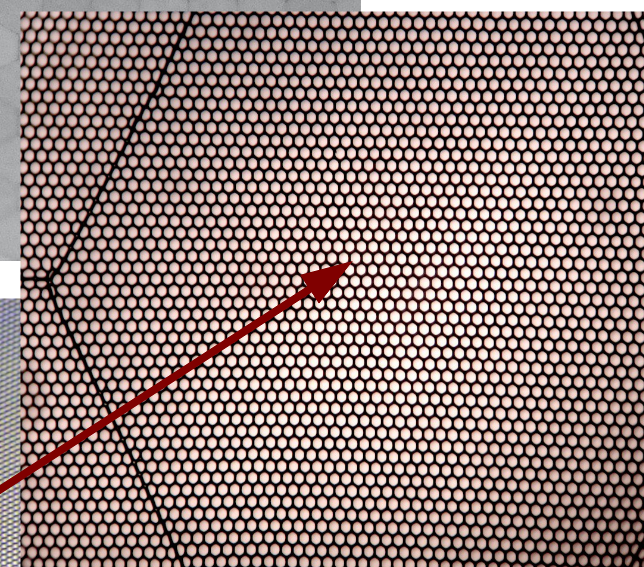
Large-Area MCPs

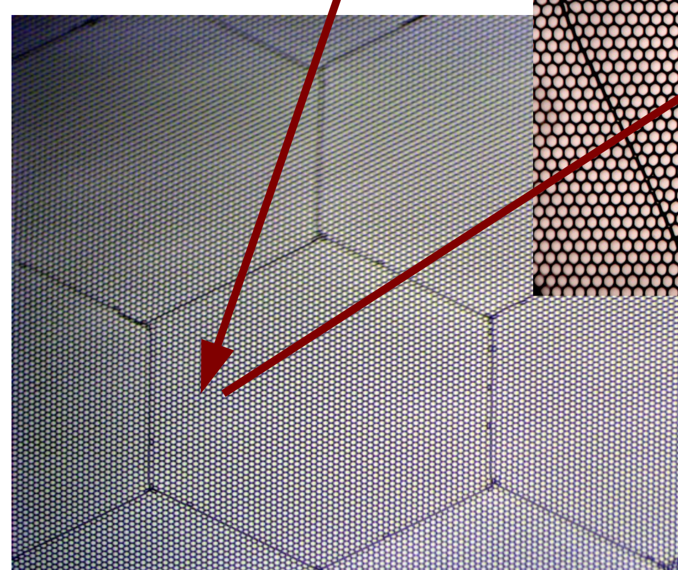
Micro-Capilary Arrays by Incom

- ***Material:*** ***borosilicate glass***
- ***Area:*** ***20x20cm^2***
- ***Thickness:*** ***1.2mm***
- ***Pore size:*** ***20 μm***
- ***L/D ratio:*** ***60:1***
- ***Open area:*** ***65-83%***



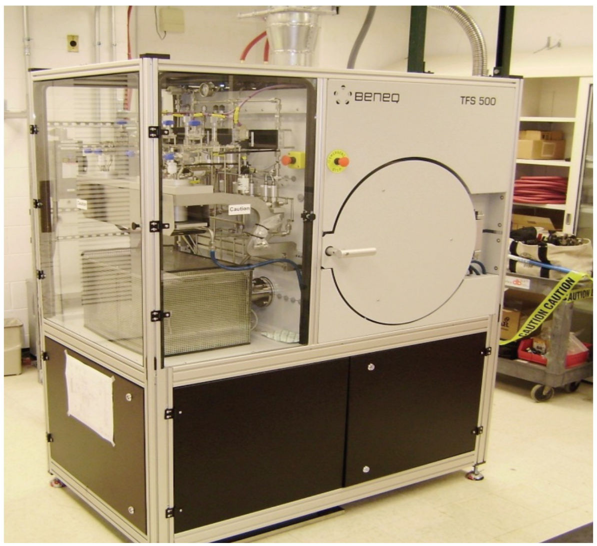


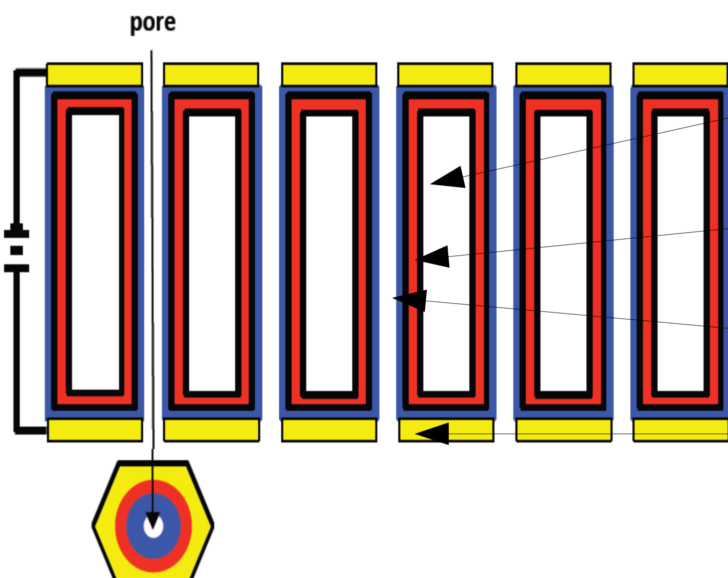




MCP by Atomic Layer Deposition (ALD)

Beneq reactor for ALD @Argonne National Laboratory





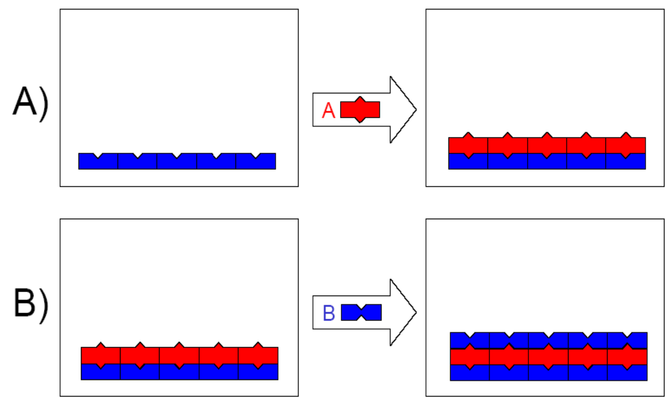
Porous glass

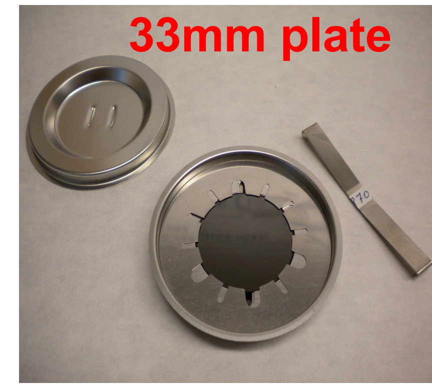
Resistive coating ~100nm (ALD)

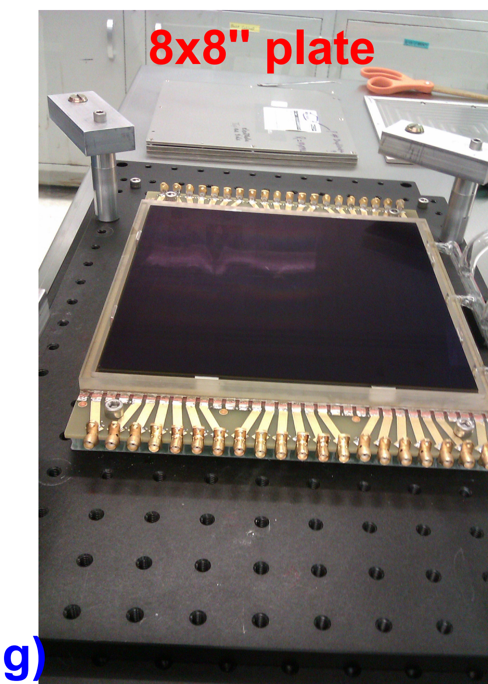
Emissive coating ~ 20nm (ALD)

Conductive coating (thermal evaporation or sputtering)

ALD Process for MCP Coating Developed by A.Mane, J.Elam







System Integration: "Demountable"

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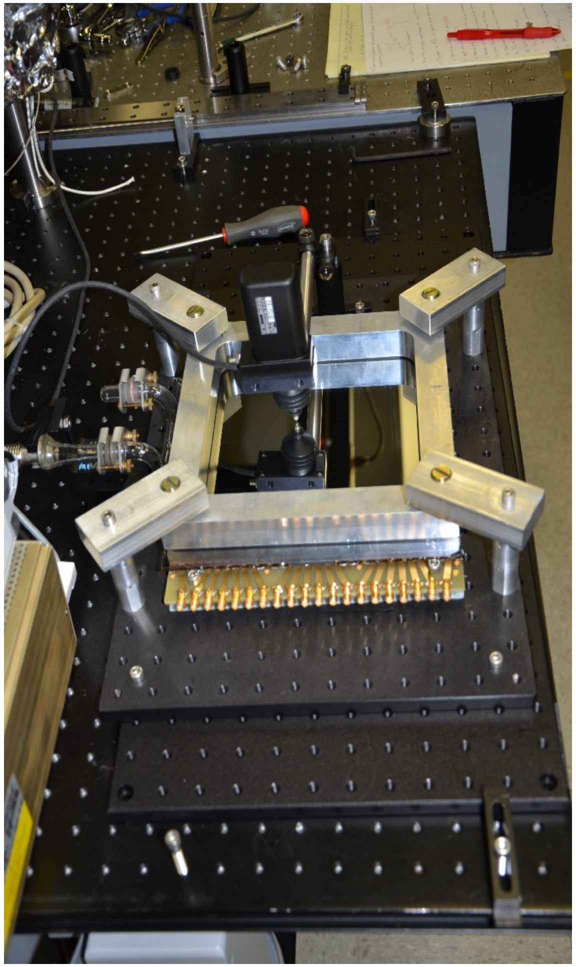
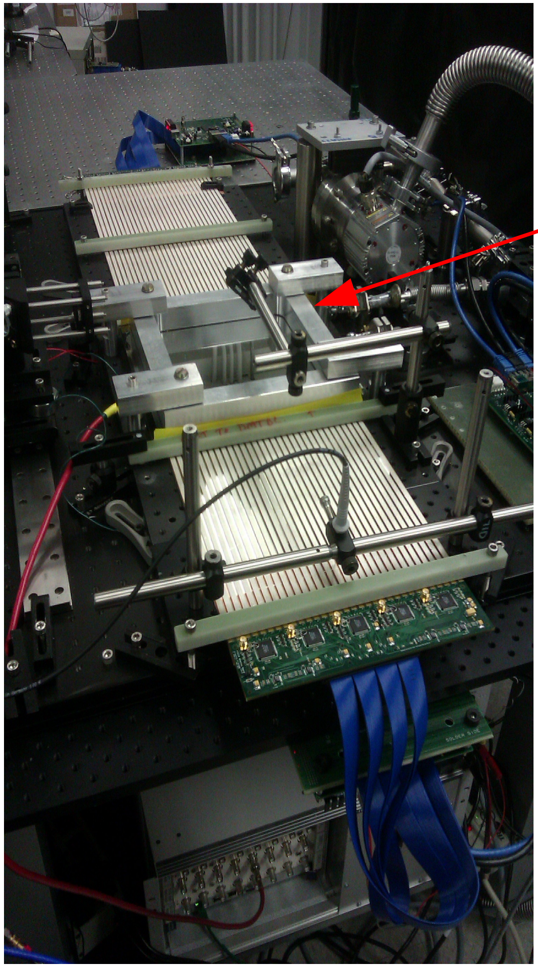
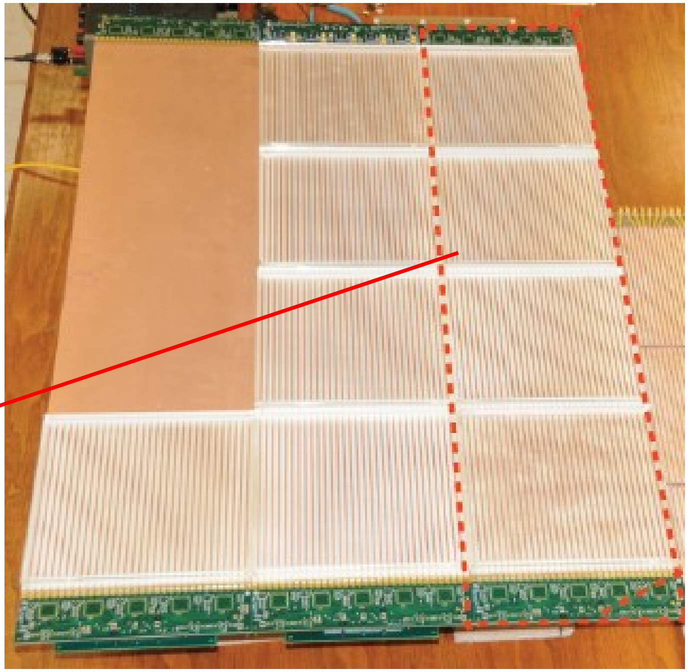
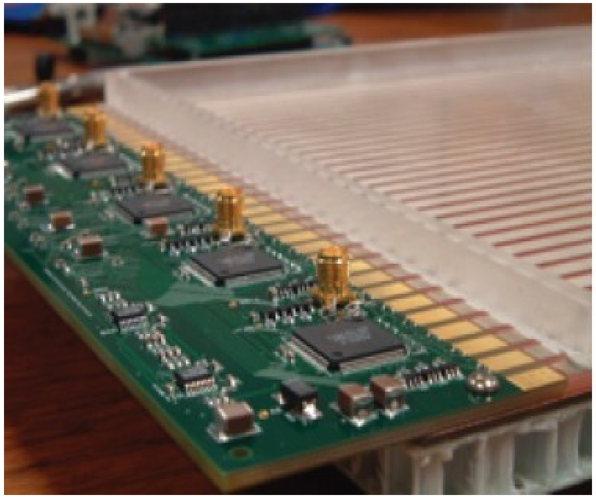
Demountable 1.0 (May 2012)

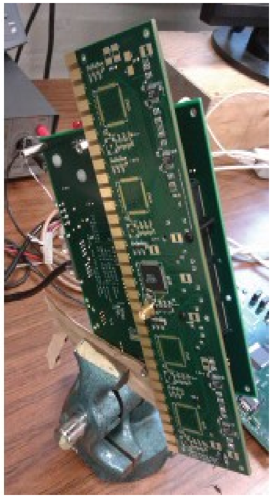


Demountable 3.0 (Sep-Dec 2012)







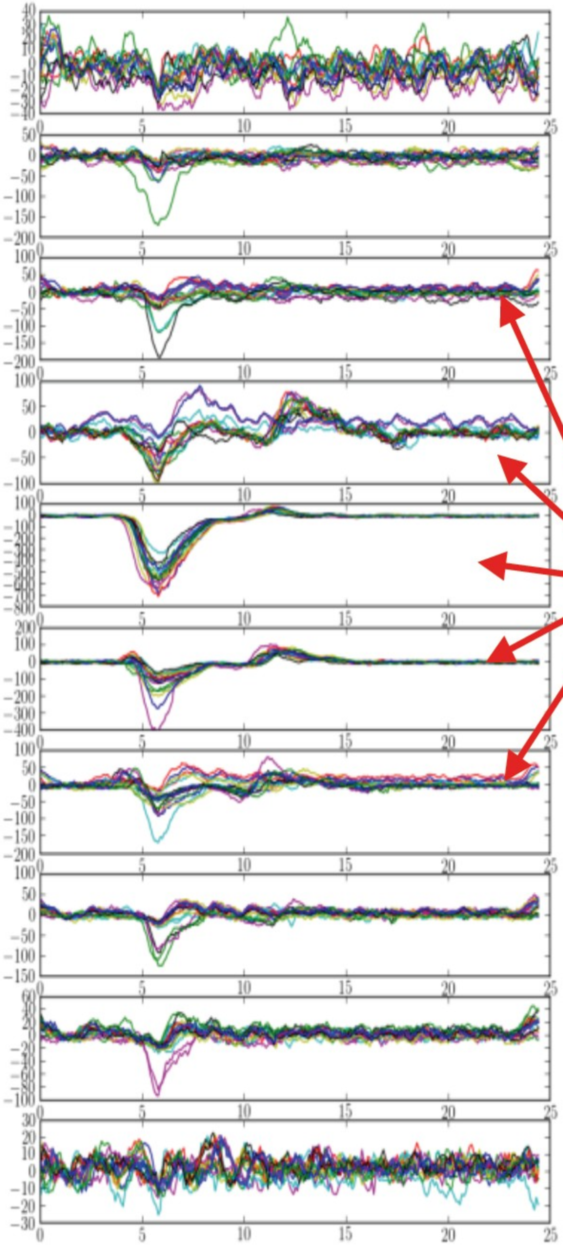


Performance

University of Chicago

Pulses on 10 striplines

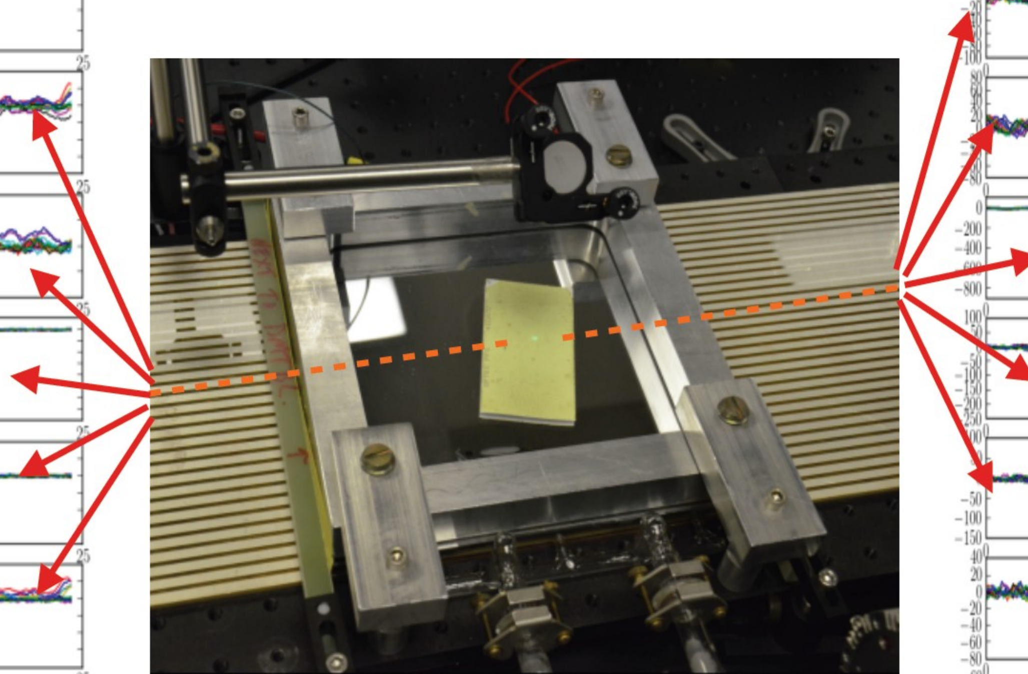
Left Side



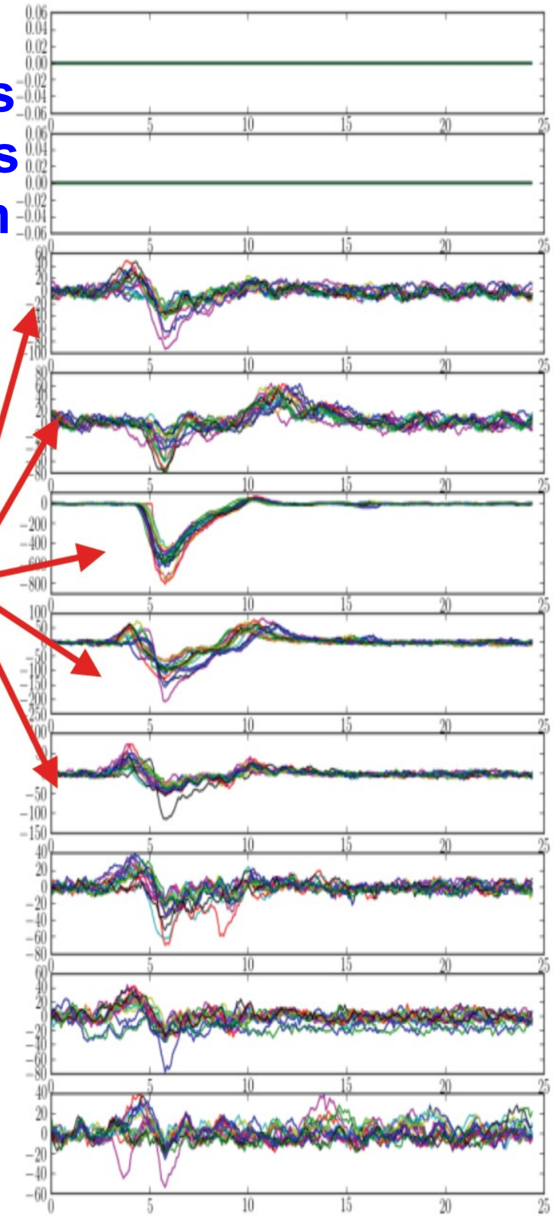
Differential time resolution up to **~ 5ps**

Time-of-flight resolution **~ 60ps**

Spatial resolution **< 1mm**



90cm long anode!

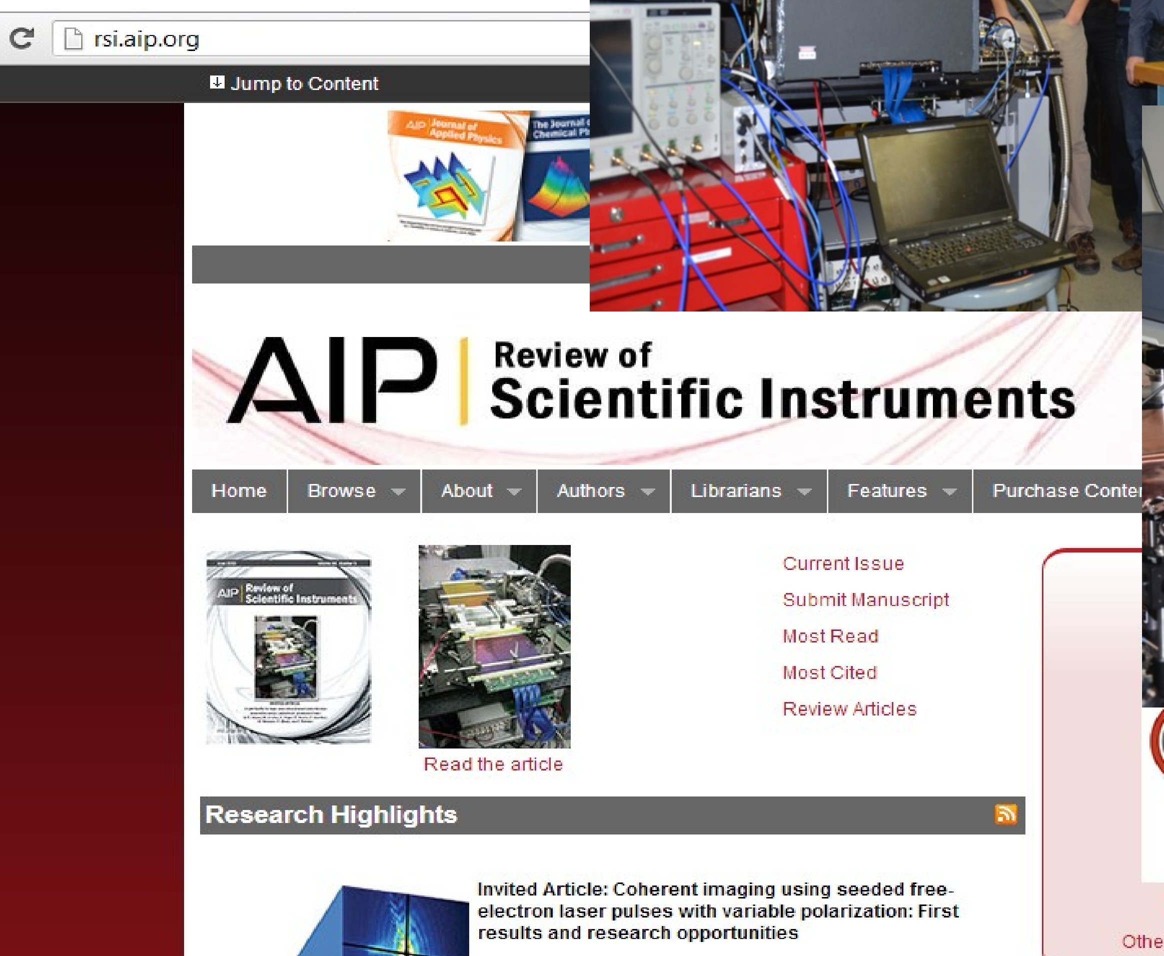


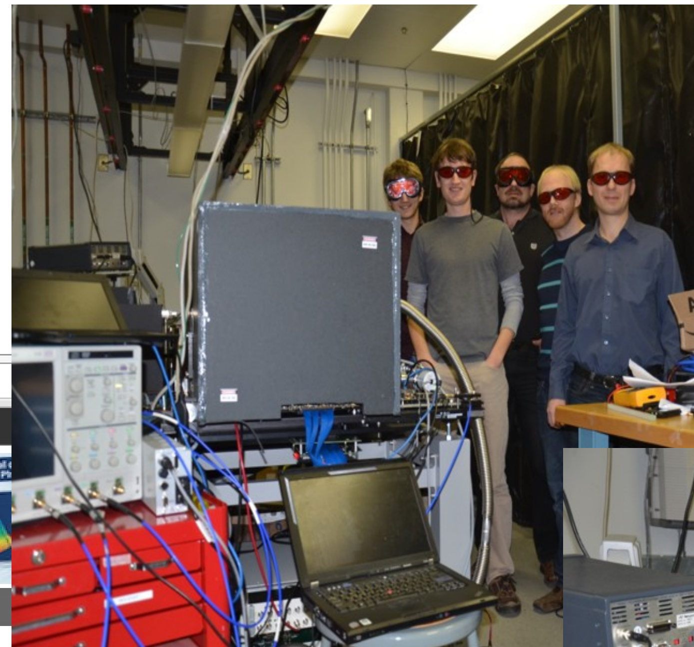
Right Side

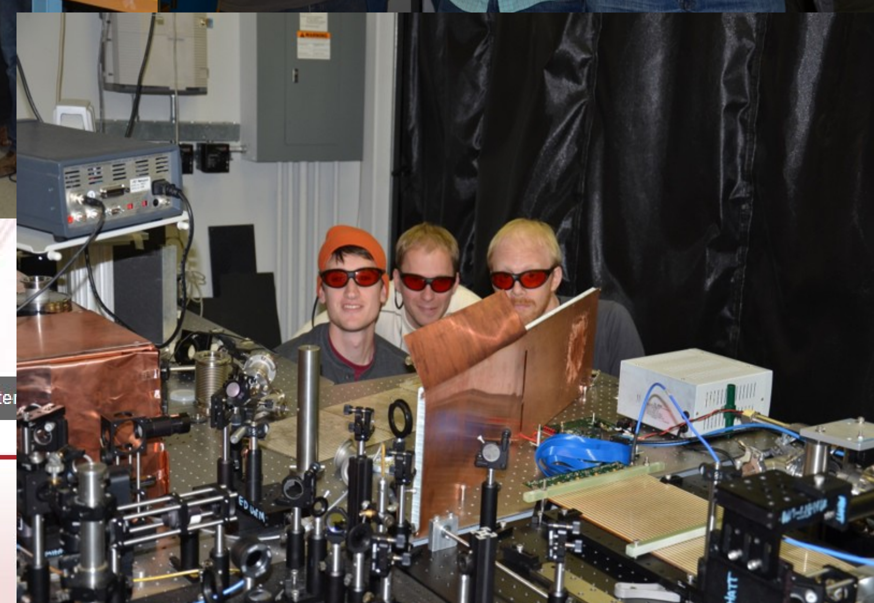
Pulses on 10 striplines

RSI Invited Article

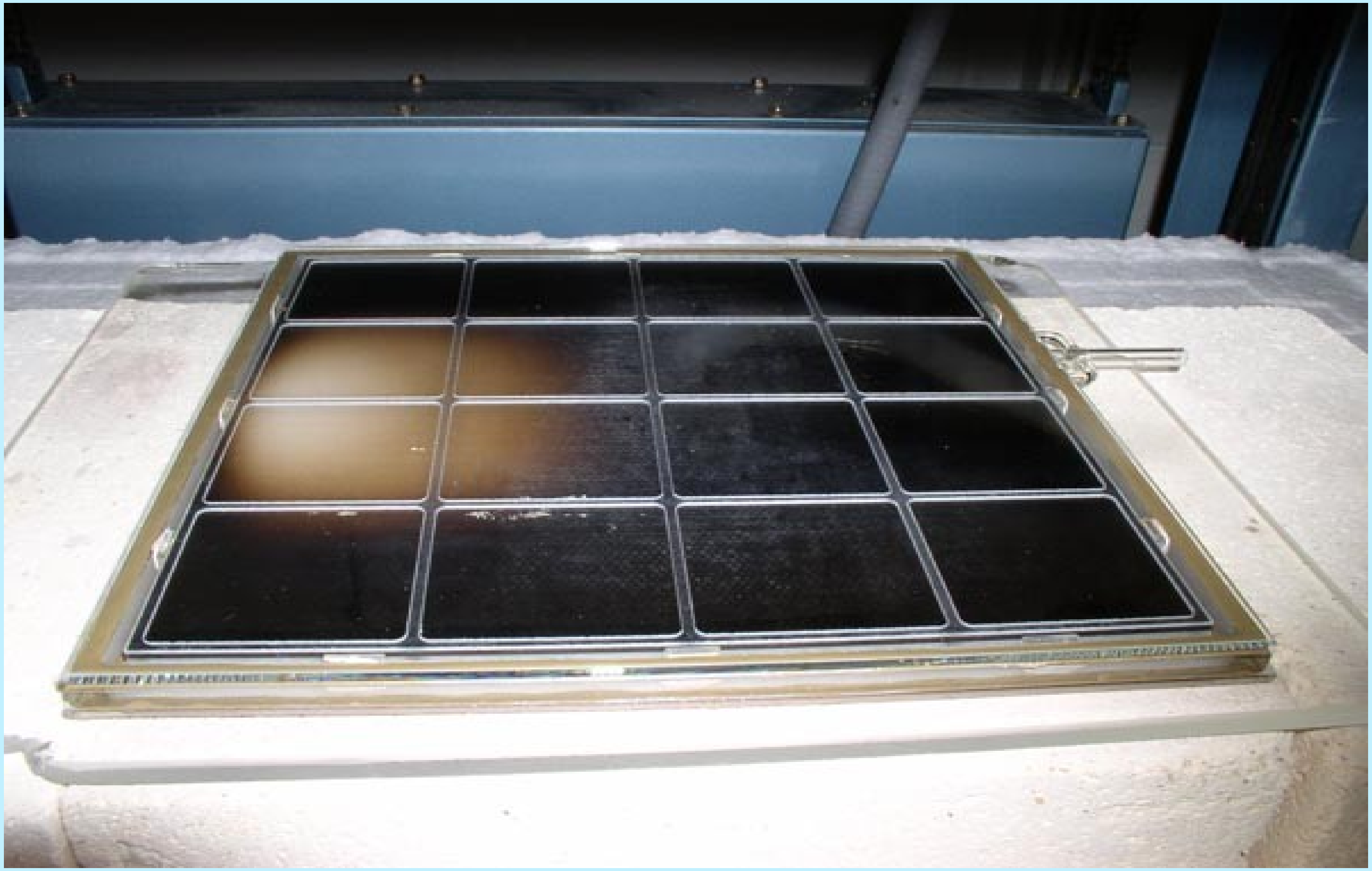
Rev. Sci. Instrum. 84, 061301 (2013)







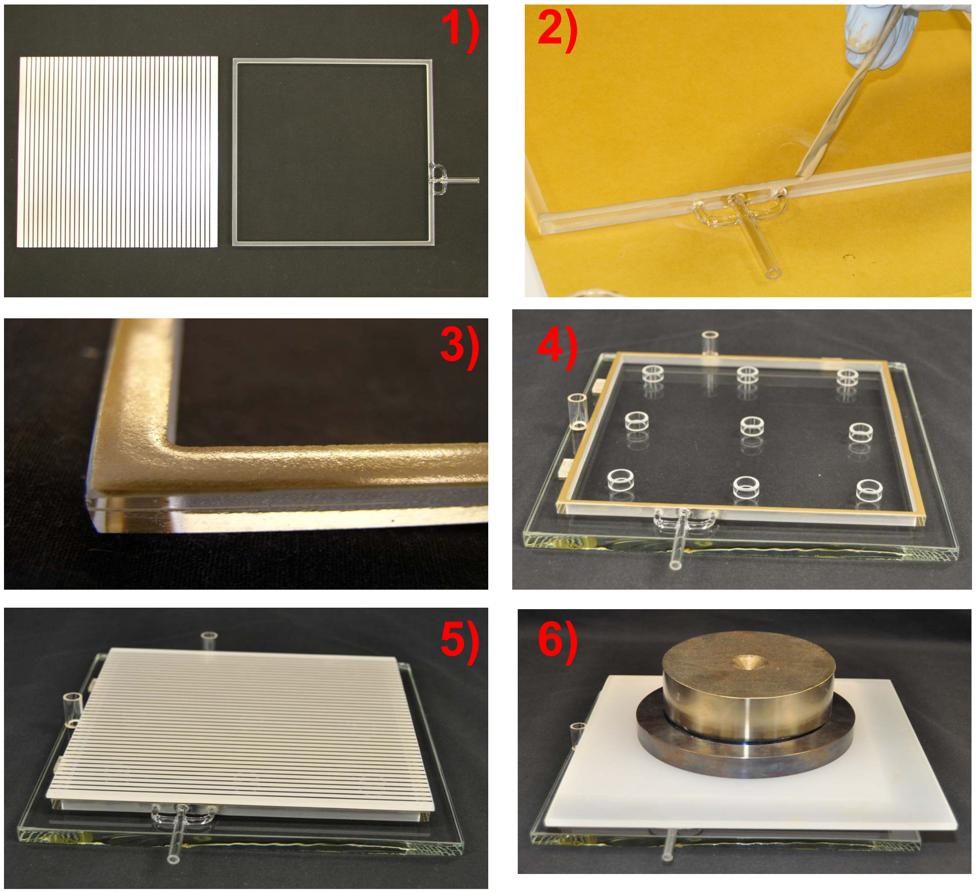
Hermetic Packaging



Frit Seal

University of Chicago

J.Gregar, M.Minot



1) Attach pump out tube to 8.66x8.66" frame

2) Apply schott #G018-223 K3 frit paste to frame

3) Fire the frit (many trials to optimize parameters)

4) Prepare for anode plate frit sealing

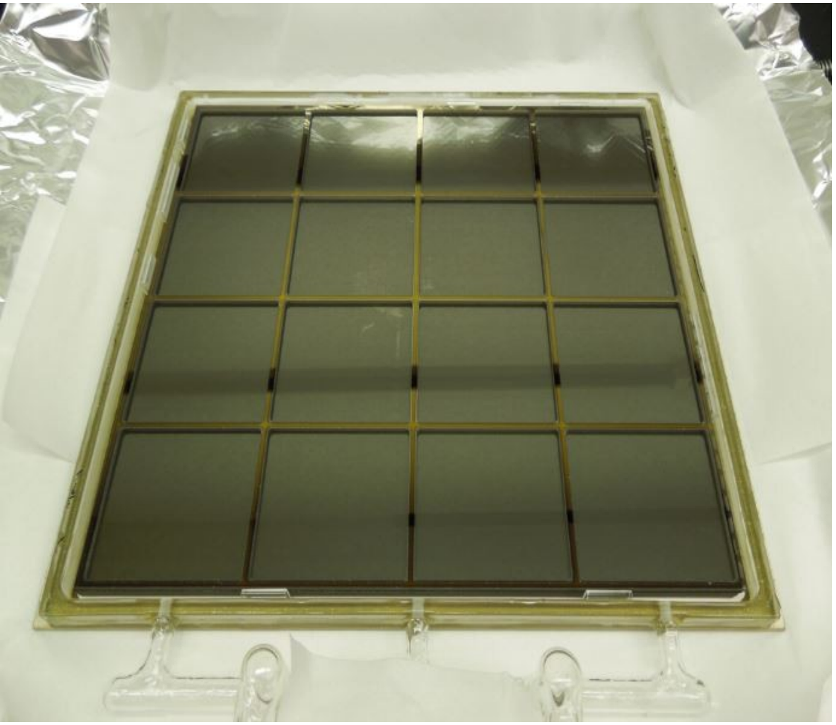
5) Position anode on top of the frame

6) Add weight

- Tile bases are reliably reproducible
- Mechanical and vacuum properties have been tested

Top Seal

How to close frit sealed tile base at the top and stay at moderate temperatures? "Top Seal" problem

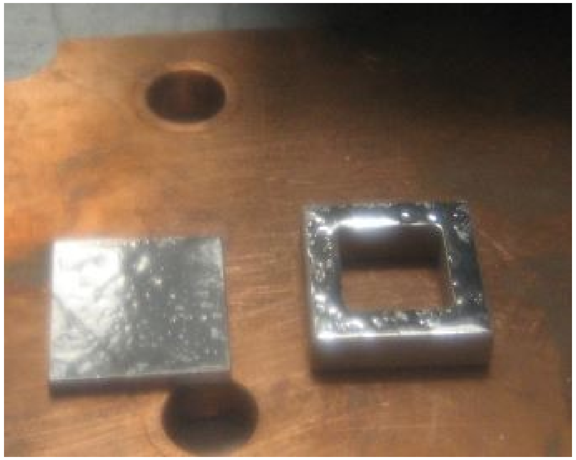


Use indium or indium alloys
- soft metal
- low melting point (157C for pure In, 72C for InBi)
- essentially zero vapor pressure
- indium-glass seals are successfully used by industry

Parallel efforts: „Hot Seal“ and „Cold Seal“ (or “Compression Seal“)

Hot Seal

Step 1:
apply melted indium onto the glass



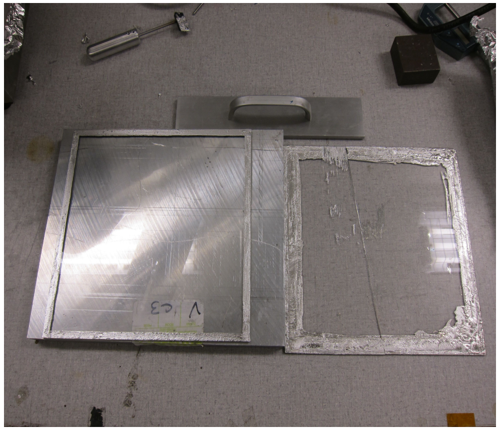
Step 2:
bring parts into contact and press

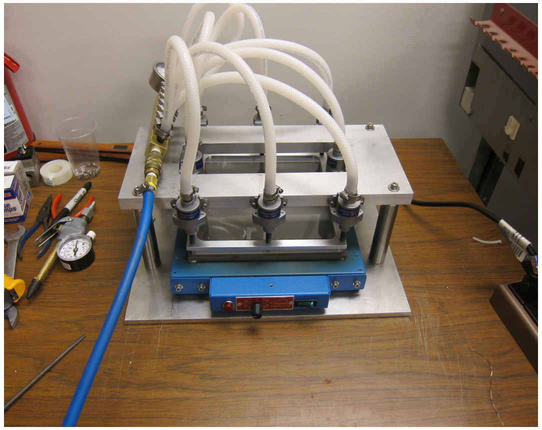
Step 3:
pump from open side and leak check

Prerequisites for leak-tight seal

- **Strong Indium-Glass bond**
- **Strong Indium-Indium bond**

Phase I (in air)





A.E., Henry Frisch, Mary Heintz, Bob Metz, Richard Northrop, Razib Obaid

- **Indium seal fundamentals**
  - interface (good adhesion of indium to the glass surface)
  - oxide formation

- **Proof of principle using 1x1" test samples**
  - little oxidation (assembly is fast)
  - many successful reproducible leak tight samples

- **Several (>10) attempts to make 8x8" seal**
  - oxide formation becomes limiting factor (slow assembly)
  - best result is a part with 10^{-6}cc/s leak at a single pinpoint

...indium oxidizes quickly...

Phase II (in inert atmosphere)

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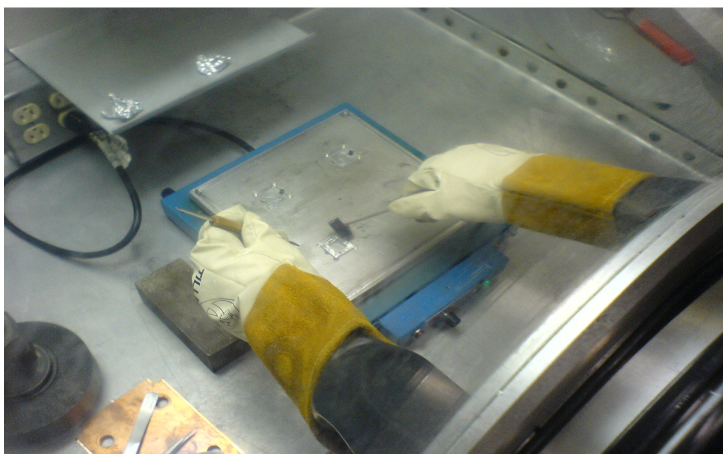
Phase IIa (in inert atmosphere)

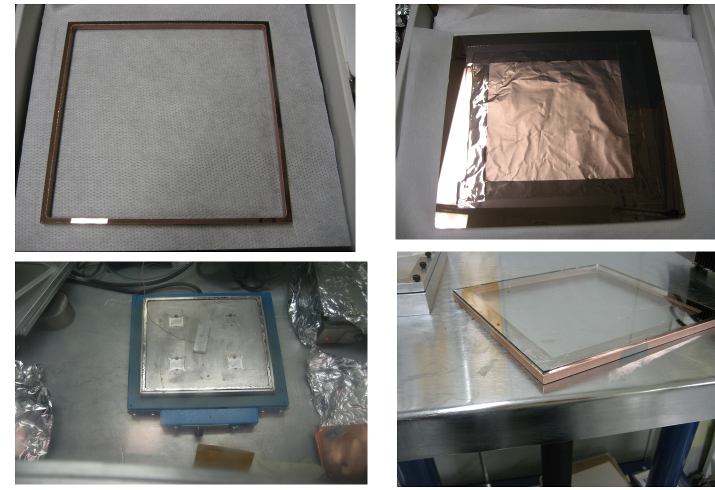
Nitrogen filled glove box:

O_2 and H_2O concentration ~5ppm



...indium doesn't stick to glass if no O_2...

Phase IIb (add NiCr-Cu layer)



Borrowed from SSL seal
(200nm of NiCr+Cu)

Known facts:

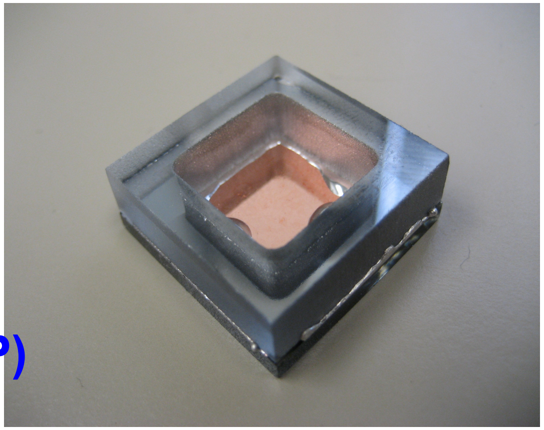
- **Indium wets copper surface**
  - *Alloy is formed at the interface over time*
- **NiCr interface to glass is essential**
  - *NiCr is a good match to glass in terms of thermal coefficient*
  - *Cu would not stick to bare glass but does so on NiCr*

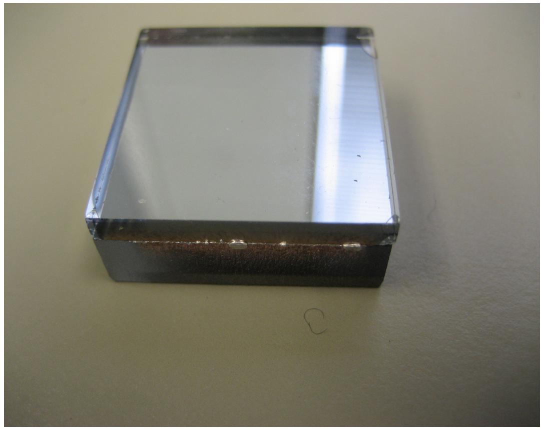
Testing NiCr-Cu-In Interface

University of Chicago

Total 8 small size seals made: 5 are leak tight
3 have leaks (oxidation of Cu surface or electroding peeling off the glass)

NiCr-Cu coating of
1" samples done by
D. Walters (ANL)
M. Kupfer (UIC)
J. Williams (ANL-HEP)
C. Liu (ANL-APS)
Q. Guo (UChicago MRSEC)





Shear tests results

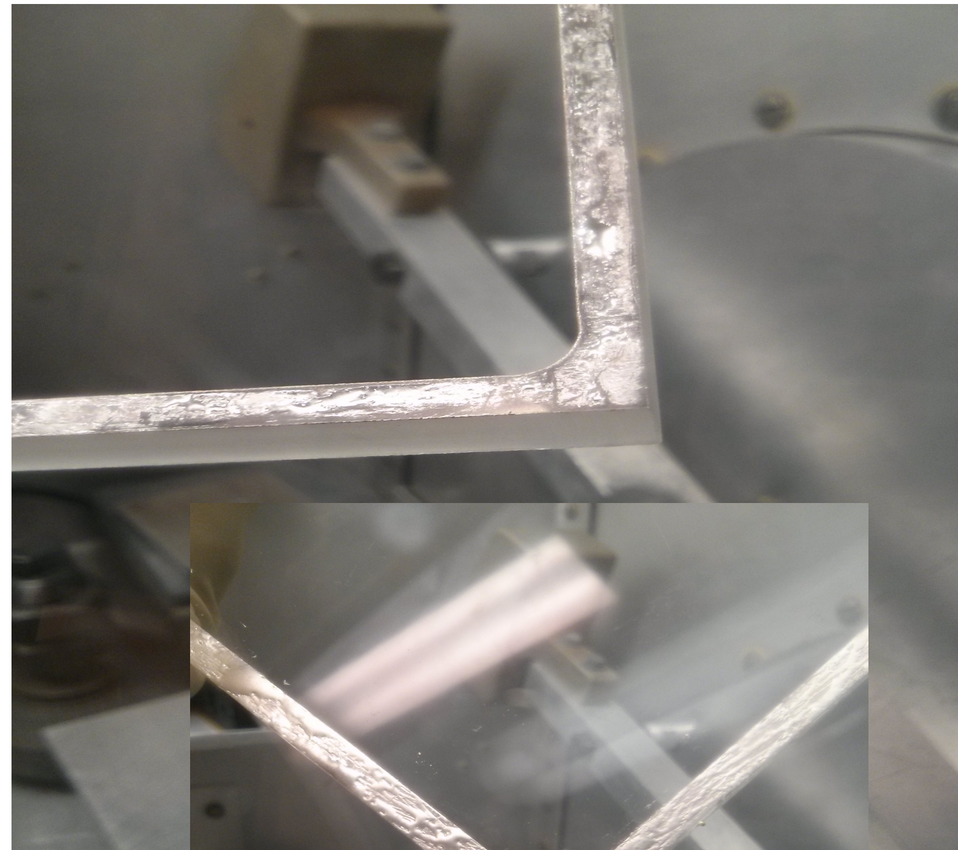
Leak tight samples:

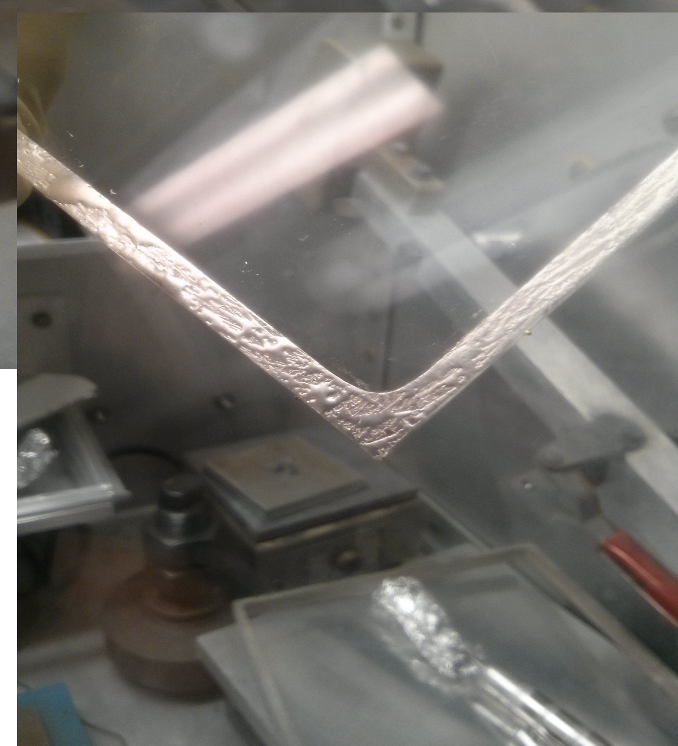
Bare glass #1	190 lbs
Bare glass #2	278 lbs
Bare glass with groove	268 lbs
Cu coated glass #3	390 lbs
Cu coated glass #4	345 lbs

Samples with a leak:

Bare glass #4	47 lbs
Cu coated glass #1	213 lbs
Cu coated glass #2	221 lbs

Sealing 8x8" parts





Testing NiCr-Cu-In Interface

University of Chicago

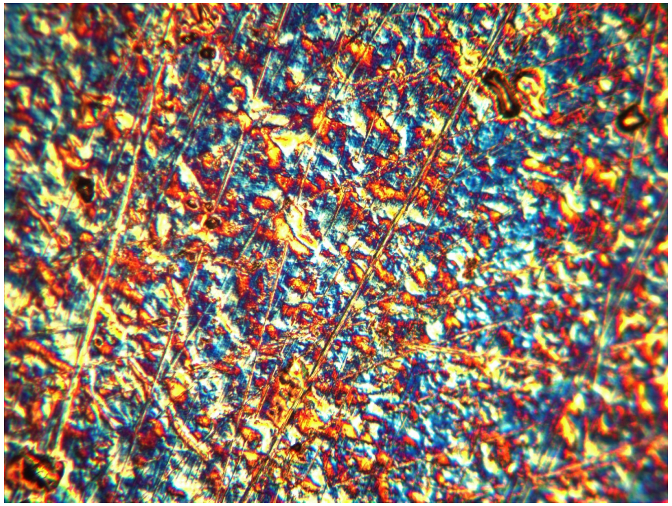
Coating goes away if re-heated to 180C

Photos from Metallurgical Microscope (by H.L.Clausing)

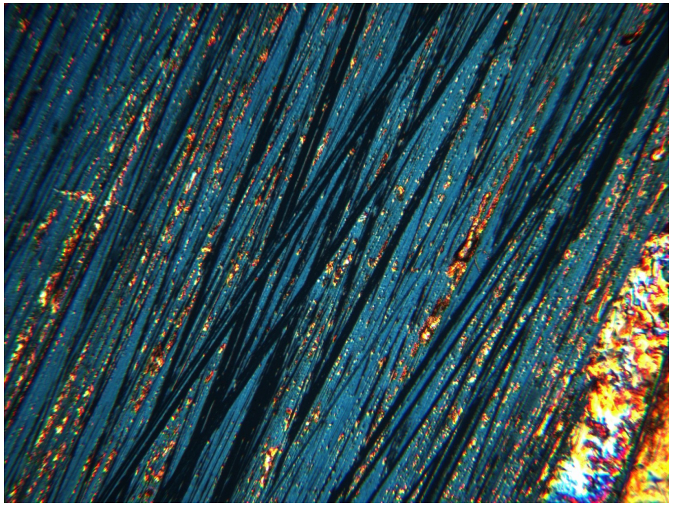
University of Chicago

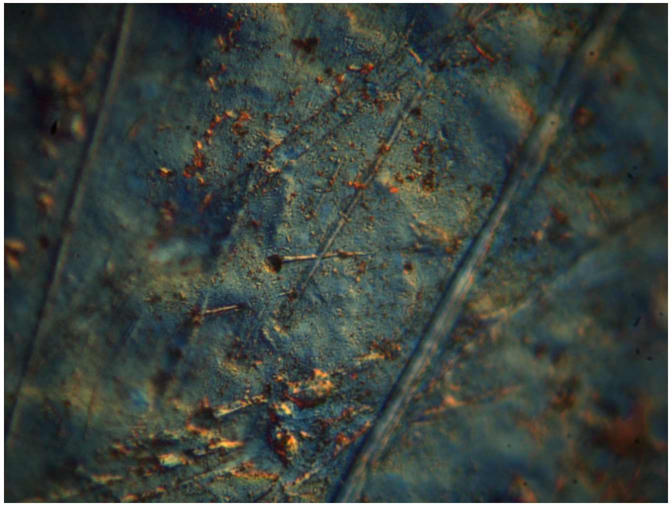
Thick side

Thin side

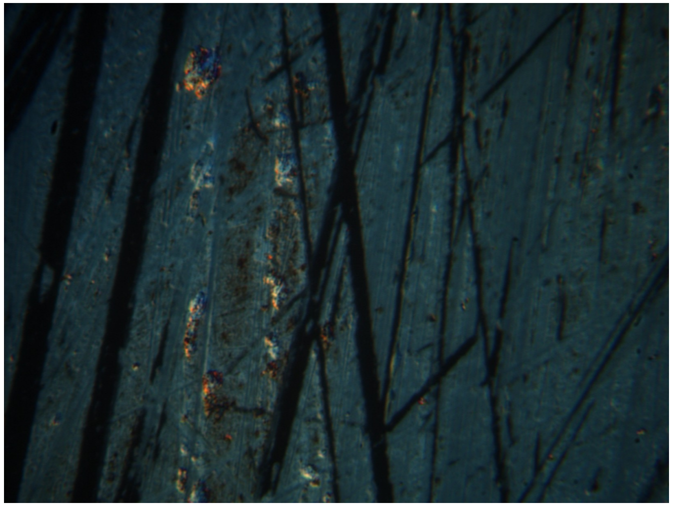


x200





x1000



Cu layer dissolves in indium

Solution

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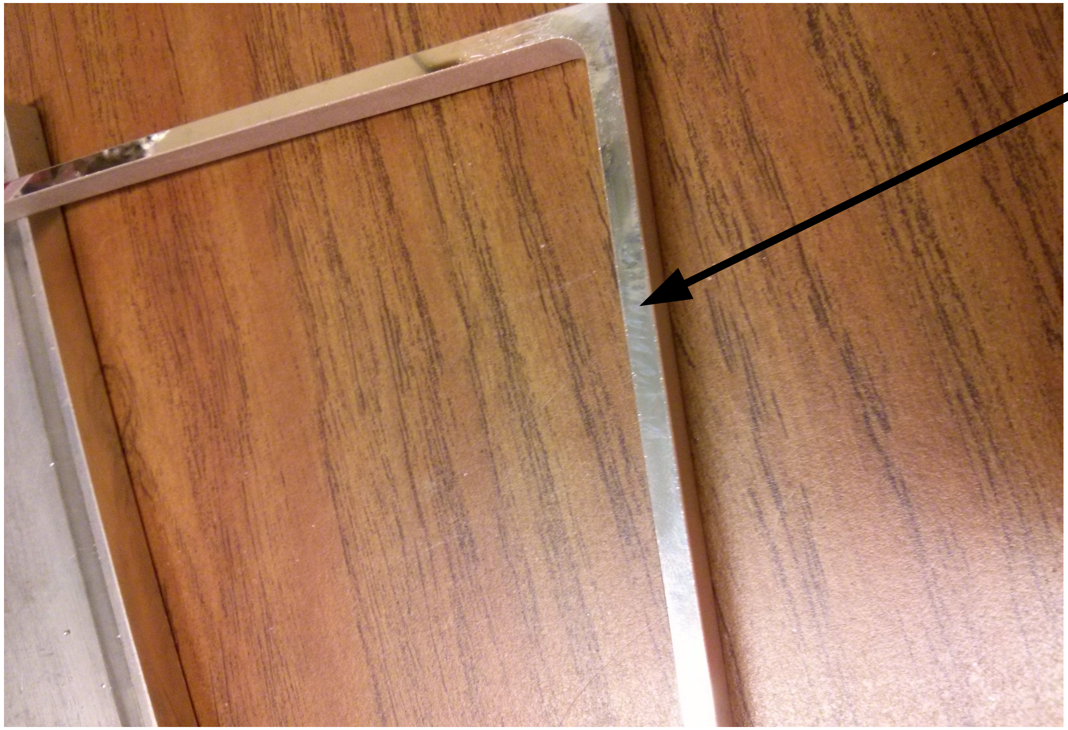
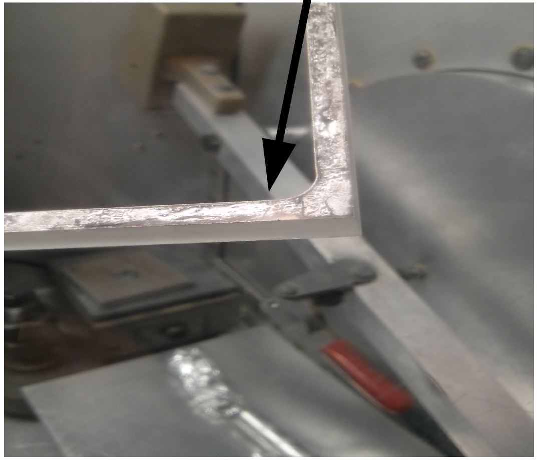
Switched to InBi alloy (melting point 72C)
No signs of Cu scavenging by InBi

Why pure In works on 1x1“ samples?
- faster assembly (less time at high temperature)
- less mechanical rubbing

InBi wetting test



Compare pure In



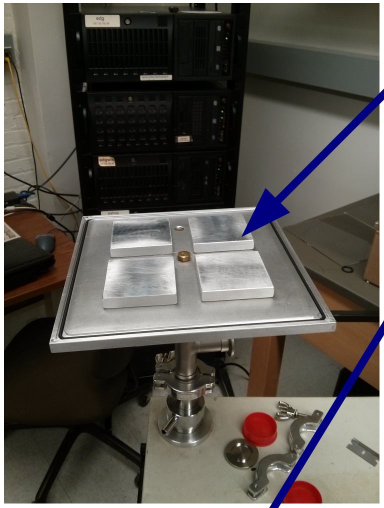
$400cm^2$ seal with 2.75 mm window

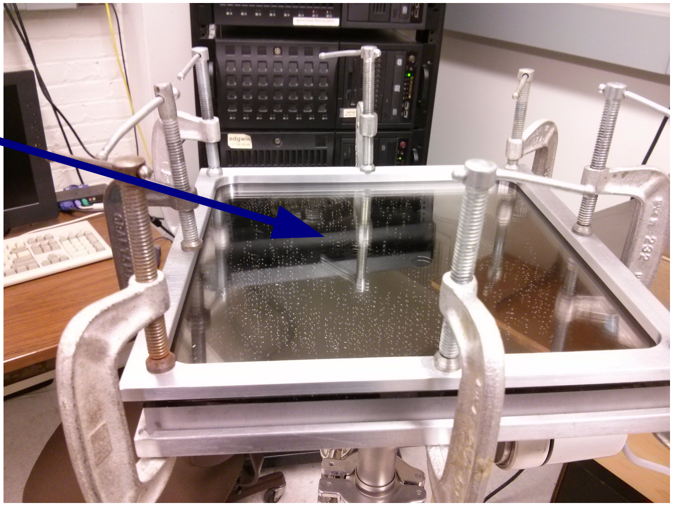
First leak tight 8x8“ seal using LAPPD glass parts

Leak Test

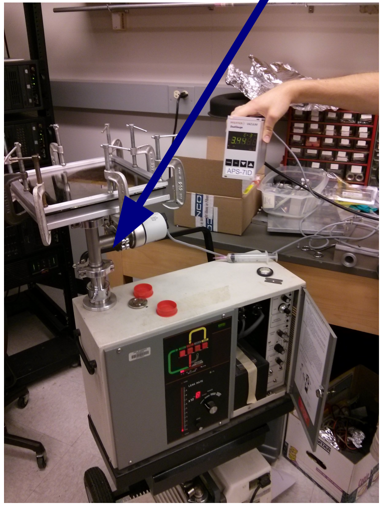
University of Chicago

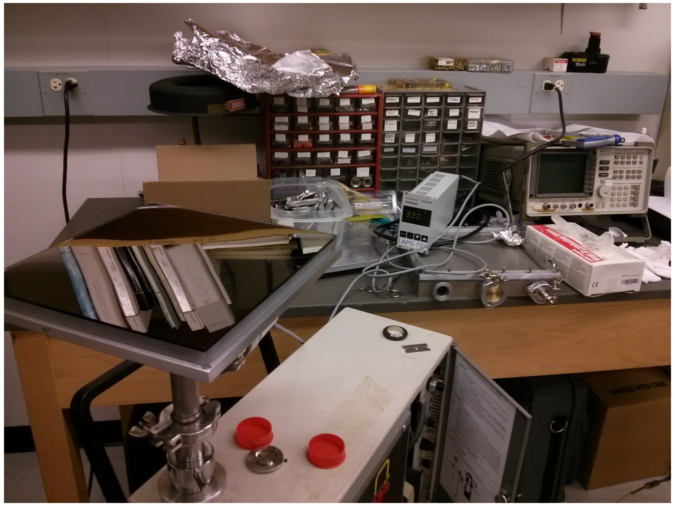
Many tricks to avoid glass cracking when the pump starts

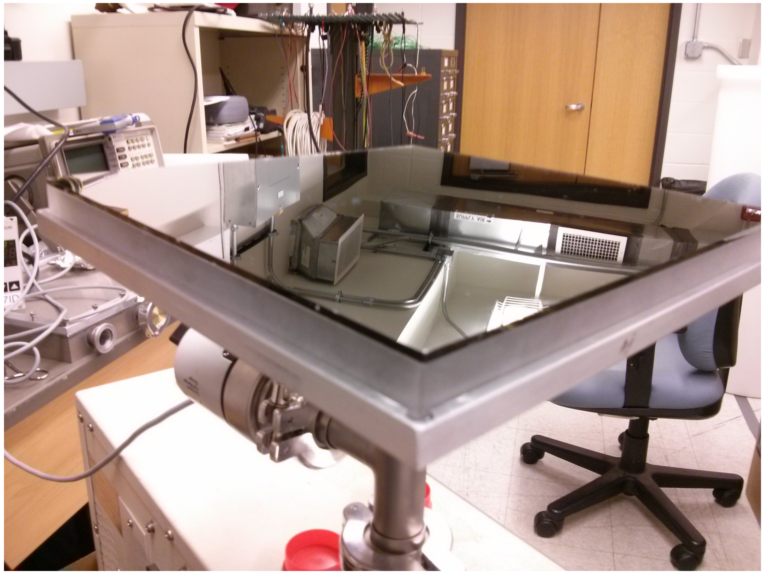




- Leak checker sensitivity 10^-8 cc/s of He
- Leak test lasted for 1 hour
- No leaks found!







Next Steps

- **Test reproducibility of the"hot seal" recipe**
- **Move forward with tile assembly**
- **Try to make photo-cathode by In-Situ Photo-Cathode Synthesis** (possible lunch topic)